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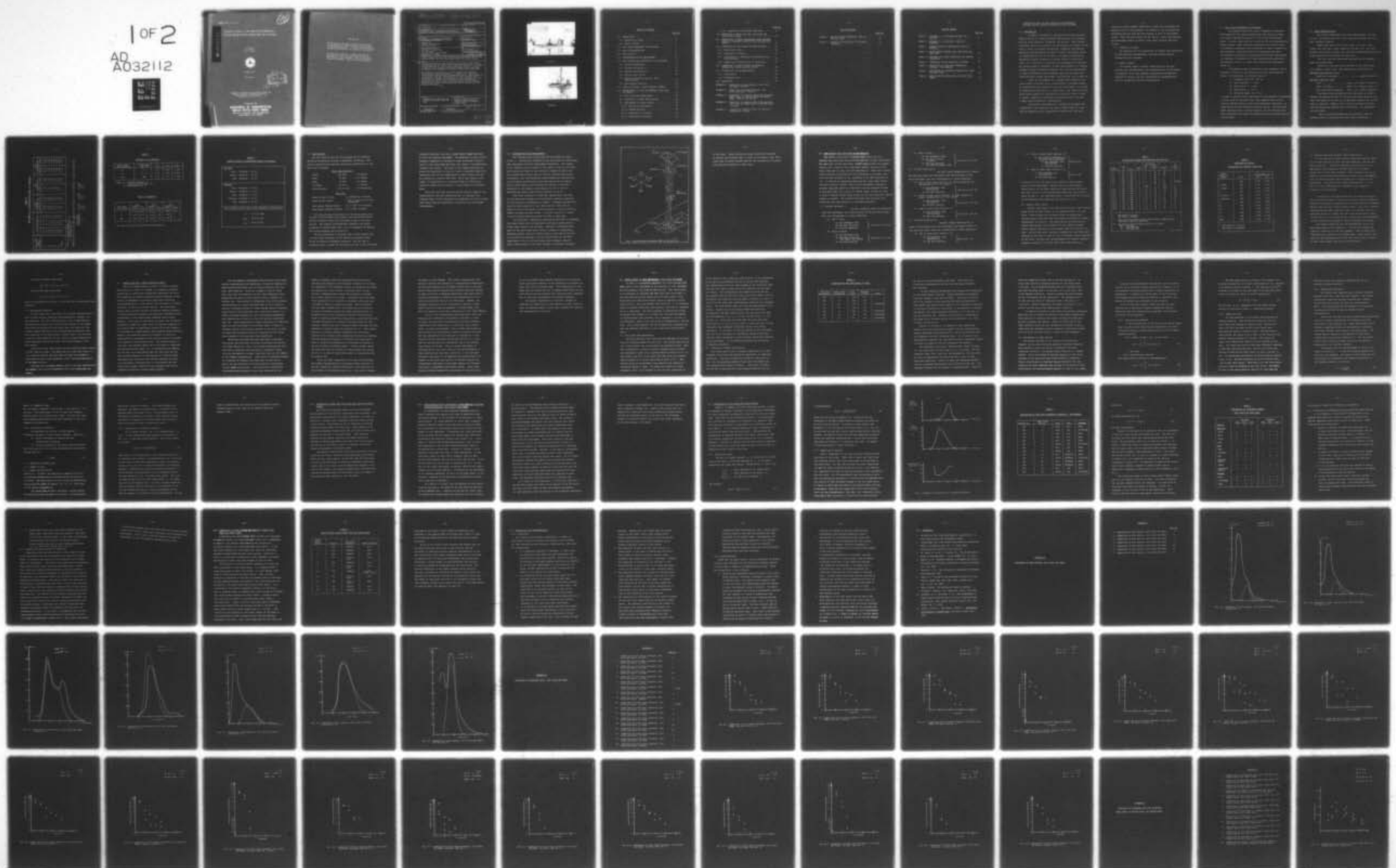

Report No. CG-D-52-76

FEASIBILITY STUDY OF TANK MODELING ENVIRONMENTALLY AFFECTED LOADING RELATED RECREATIONAL BOAT ACCIDENTS

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DEPARTMENT OF TRANSPORTATION UNITED STATES OF AMERICA

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16. Abstract

The objective of this report was to evaluate the feasibility of tank modeling environmentally affected loading related recreational boat accidents. Full scale accident simulations for a jon boat and a runabout were modeled in a test tank. A comparison of full scale/model scale motion decrement curves was performed. RAO linearity was investigated for both models in head and beam regular waves.

The feasibility of tank modeling full scale accidents has not been fully established by the present investigation. In particular, the comparison of full scale/model scale incidences of shipping water was poor. Most discrepancies are attributed to problems in documenting the full scale environment and/or reproducing it in the tank. Wave directionality, shape, frequency, short versus long crested seas, and wind are all discussed as possible problem areas. Nevertheless, the ability to match a large proportion of the various measured motions provides a basis for expecting improved modeling capability when these factors are considered.

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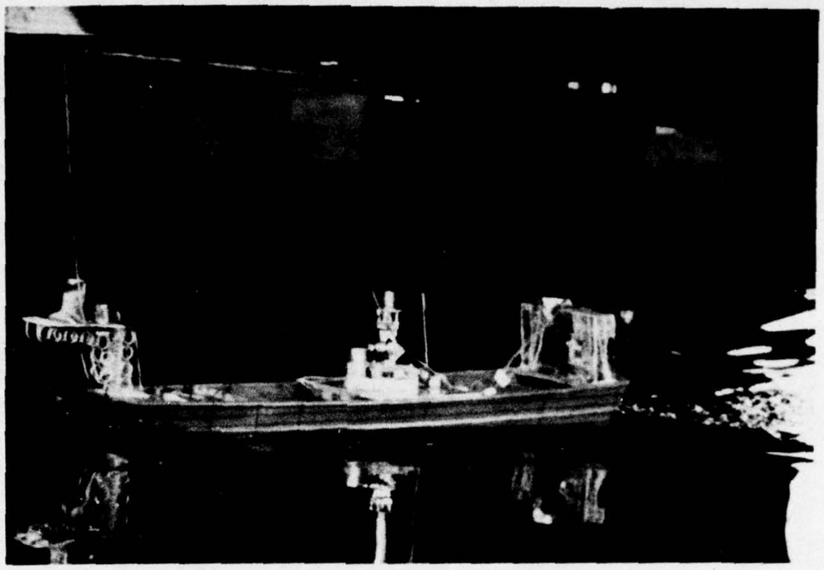
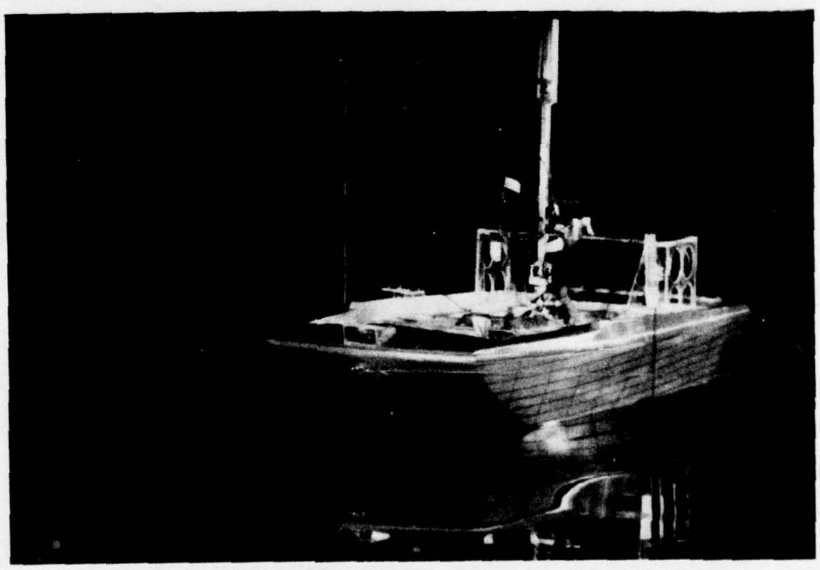


JON BOAT



RUNABOUT

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FEASIBILITY STUDY OF TANK MODELING ENVIRONMENTALLY AFFECTED LOADING RELATED RECREATIONAL BOAT ACCIDENTS

1.0 INTRODUCTION

A number of accidents in recreational boating have been found to be due to "loading related" effects which are connected with the craft stability, freeboard, and motions. These various influences involve the effect of the distribution of loading of the craft; a shift in loading; insufficient freeboard; insufficient stability; and the effects of waves (or wakes from passing boats) in combination with all of the above. In order to establish an appropriate loading standard for various types of recreational craft, it is important to establish the parameters that influence the various types of accidents, so that establishment of a loading standard, minimum allowable freeboard, etc., can be characterized in terms of significant major elements such as craft size, wave characteristics (length and height), pitch period, roll period, etc.

Since the environment (i.e. ambient wave system) is not controllable in any full scale investigations, a proposed method of investigating the influence of the wave environment is by means of modeling and simulation in a towing tank. The results obtained could then be applied to available full scale test data in order to obtain a measure of validation of the predictions from such a model testing simulation investigation.

The present investigation is intended to determine the feasibility of this approach, by means of model tests in a test tank and comparison with representative results for full size

recreational boat accident conditions, as well as to determine the possible limits of such methods. An outline of the techniques and procedures that are used for this purpose is given in the present report. This work was carried out for the U.S. Coast Guard Research and Development Center in Groton, Conn. under Contract DOT-CG-81-75-1427.

1.1 Objective of Study

The objective of this program was to evaluate the feasibility of tank modeling environmentally affected loading related recreational boat accidents.

1.2 Report Content

The present report includes a description of the test facility and instrumentation; the characteristics of the models; a discussion of the test program, conditions and parameters; analysis of results; and the conclusions and recommendations that are determined from this investigation.

2.0 FULL SCALE PARAMETERS TO BE MODELED

The present feasibility study is supposed to establish some measure of the capabilitiesof model tank testing in waves as a means of predicting behavior of full scale recreational boats. As such, tests would be carried out for two representative types of boats, under conditions representing the actual range of parameters considered to be significant in their influence on boat response. These conditions also represented the basic environmental and physical characteristics that were experienced (or expected) in separate full scale investigations carried out by personnel of the U. S. Coast Guard Research and Development Center [1].

The expected range of these full scale parameters, which provides an overlap of the conditions for both representative boats, is listed below, as obtained from [2].

(1) Passenger load, 100 - 800 lb.

(2) Boat velocity, 0 - 5 mph

(3) Wave period, 2 - 5 sec.

(4) Wave height, 1 - 6 ft.

(5) Anchoring depth, 20 - 31 ft.

In order to satisfy these requirements it was necessary to establish a proper scale of the model that, when combined with the test facility characteristics, would allow appropriate simulation (in model scale) of these physical parameter values. The particular model characteristics, scaling relation, and test facility that were selected on this basis are described in the following section of the report.

3.0 MODEL CHARACTERISTICS

Two actual recreational boat hulls were modeled. One was a 12 ft. flat bottom hard chine "jon" boat and the other was a tri-hull, bowrider runabout.

Model scale was at 0.4 of full scale, e.g. the 12 foot length "jon" boat had a model length of 4.8 feet, etc. All wave-lengths, wave height, periods, etc. were then approximately scaled via Froude scaling at this particular scale ratio.

The "jon" boat was fabricated from wood and the runabout from high density foam.

Drawings of both hulls were provided by the Coast Guard R & D Center, Groton, Conn. The drawings were identified as:

JON BOAT, Test Hull No. 75-15

Lines and Arrangement .... dated 26 June 75

TRI-HULL, Test No. 73-18

Lines .... Sheet 1 of 3 dated 10 March 75

Table of Offsets .... Sheet 2 or 3 dated 26 June 75

Deck Lines and Arrangement .. Sheet 3 of 3 dated 11 March 75

The models were ballasted so that the center of gravity matched the desired location of the full scale boats while at the same time achieving as close as is reasonably possible the desired radii of gyration. Tables 1 and 2 lists the centers of gravity and the desired and achieved radii of gyration. All dimensions are full scale.

Table 3 lists the assumption for individual radii of gyration used in calculating the total radii of gyration.

TABLE 1

JON BOAT C.G. LOCATIONS AND RADII OF GYRATION

Coast Guard Load Conditions	C.G. Location, ft.			Pitch Gyradius, ft.		Roll Gyradius, ft.		Yaw Gyradius, ft.	
	x	y	z	Desired	Actual	Desired	Actual	Desired	Actual
1	1.14	0.0	1.60	4.268	4.215	1.105	1.318	4.223	4.330
2	-1.17	0.0	1.46	3.118	3.180	1.110	1.243	3.024	3.010
14	2.66	0.0	1.57	3.895	3.980	1.14	1.438	3.823	3.970
15	-2.78	-0.06	1.47	2.354	2.354	1.308	1.518	2.356	2.625
4	-0.13	-0.03	1.62	3.975	3.938	1.305	1.283	3.975	3.853
5*	2.81	0.06	1.84	3.538	3.521	1.398	1.521	3.504	3.005
6*	-2.58	-0.06	1.43	2.321	3.550	1.30	1.503	2.328	3.243
3(tank)	0.89	0.00	1.59	4.245	4.215	1.10	1.318	4.203	4.373

where x - forward midships, ft.
y - starboard centerline, ft.
z - above baseline, ft.

***Anchor wt.** of 60 lb. was added after boat was ballasted to these conditions. Location of weight was:

Coast Guard Load Condition	x in ft.	y in ft.	z in ft.
5	6.25	0.0	0.52
6	-4.58	0.0	0.31

TABLE 2

RUNABOUT C.G. LOCATIONS

Coast Guard Load Condition	Coast Guard Test No.	x (ft.)	y (ft.)	z (ft.)
9	9	1.12	-0.02	2.266
11	11, 13	-2.72	-0.02	2.016
RAO	RAO	-1.29	0.0	1.726

where x - forward midships, ft.
y - starboard centerline, ft.
z - above baseline, ft.

RADII OF GYRATION

Coast Guard Load Condition	Pitch Gyradius, ft. Desired	Pitch Gyradius, ft. Actual	Roll Gyradius, ft. Desired	Roll Gyradius, ft. Actual	Yaw Gyradius, ft. Desired	Yaw Gyradius, ft. Actual
9	5.790	5.643	1.980	1.878	5.840	5.260
11	4.010	4.335	1.930	1.700	4.260	*
RAO	3.960	4.105	1.640	1.708	4.220	*

*Yaw radii of gyration not checked for these conditions.

TABLE 3

ASSUMED VALUES IN DETERMINING RADII OF GYRATION

JON BOAT	
Inst.:	Gyradius = .25 ft.
Engine:	Guradius = .50 ft.
Men:	Gyradius = 1.0 ft.
RUNABOUT	
Inst.:	Gyradius = .25 ft.
Engine:	Gyradius = 1.0 ft.
Fuel:	Gyradius = .75 ft.
Battery:	Gyradius = .50 ft.
Men:	Gyradius = 1.0 ft.
Other Assumed Values Used in Mass Properties Calculations	
g	= 32.2 ft./sec.
ρ_{FW}	= 62.4 lb./ft.
ρ_{SW}	= 64.0 lb./ft.

4.0 TEST FACILITY

The test facility used for this program was the Offshore Technology Corporation located in Escondido, California. The physical specifications and wave generating capabilities of this basin are as follows.

Basin Specifications

Length	295 feet	90 meters
Width	48 feet	14.5 meters
Depth	15 feet	4.5 meters
Pit Depth	30 feet	9 meters
Carriage Speed	0-10 ft./sec.	0-3 meters/sec.

Wave Data

Range of Wave Periods	1.2 seconds to 6 seconds
Range of Wave Length	3 feet (1 meter) to 65 feet (20 meters)
Wave Height (Regular Waves)	to 2.5 feet (0.75 meters)
Wave Height (Impulsive Waves)	to 3.0 feet (1 meter)

The wide and deep cross section of the basin permits the testing of large models, with minimal side and bottom effects. The wave absorber effectively dissipates energy at all wave periods. The computer programmed Wave Generator can create irregular or pseudo-random seas, so as to reproduce the desired wave energy spectrum and distribution.

The wave generation is obtained from a signal coming from a finely tuned oscillator at the desired wave period, which drives the hydraulic wavemaker mechanism. For the case of irregular waves, a number of oscillators are set to the particular

frequencies desired, with their output signal summed and used to drive the hydraulic wavemaker. The amplitude of each of these frequency components is selected in order to provide a distribution of wave amplitudes and hence wave energy in the particular irregular wave system. This type of wave system generation is essentially equivalent to that of a sum of sinusoidal waves with frequencies that are not commensurate in their values, and the sum produces an irregular wave form. While this system is not random, it nevertheless is a practical means of simulating a realistic random sea by virtue of a finite number of sinusoidal waves.

This wave tank test facility has the ability, based on the listed physical and wave characteristics, to represent the required range of wave characteristic parameters (at the 0.4 scale ratio size) that are prescribed in section 2.0 for the present investigation.

5.0 INSTRUMENTATION AND MEASUREMENTS

The instrumentation system used for both models is shown in Fig. 1. Motions were indicated by the deflection of a particular RVDT (Rotational Variable Displacement Transducer). The support or pin location was not exactly at the center of gravity of either model during the tests so that there was coupling of pitch into the recorded heave motion and yaw into the recorded sway motion. Furthermore, this instrumentation system senses pure surge motion as pitch motion and similarly, pure sway motion as roll motion. Both of these effects were corrected at Oceanics in the data processing of the magnetic tape supplied by OTC in order to determine the actual craft motions relative to the CG.

Some minor restraint in surge was imposed using very soft springs that were attached in the horizontal direction (parallel to the direction of propagation of waves). Different springs were used for surge restraint at zero speed and for conditions at speed in view of the greater forces necessary to restrict drifting effects at speed for both models. A similar situation in regard to use of spring restraints exists for sway in beam seas.

For each model, appropriate calibrations were made to determine the signal levels that corresponded to particular deflections in surge, heave, pitch, roll and sway. Similarly calibrations were made for the wave height probe (which is based on a capacitance measuring system) that was located closer to one side of the tank in line with the location of the CG of each model for the zero speed case, as well as for the probe used to measure relative motion (with respect to the motor surface) at different locations

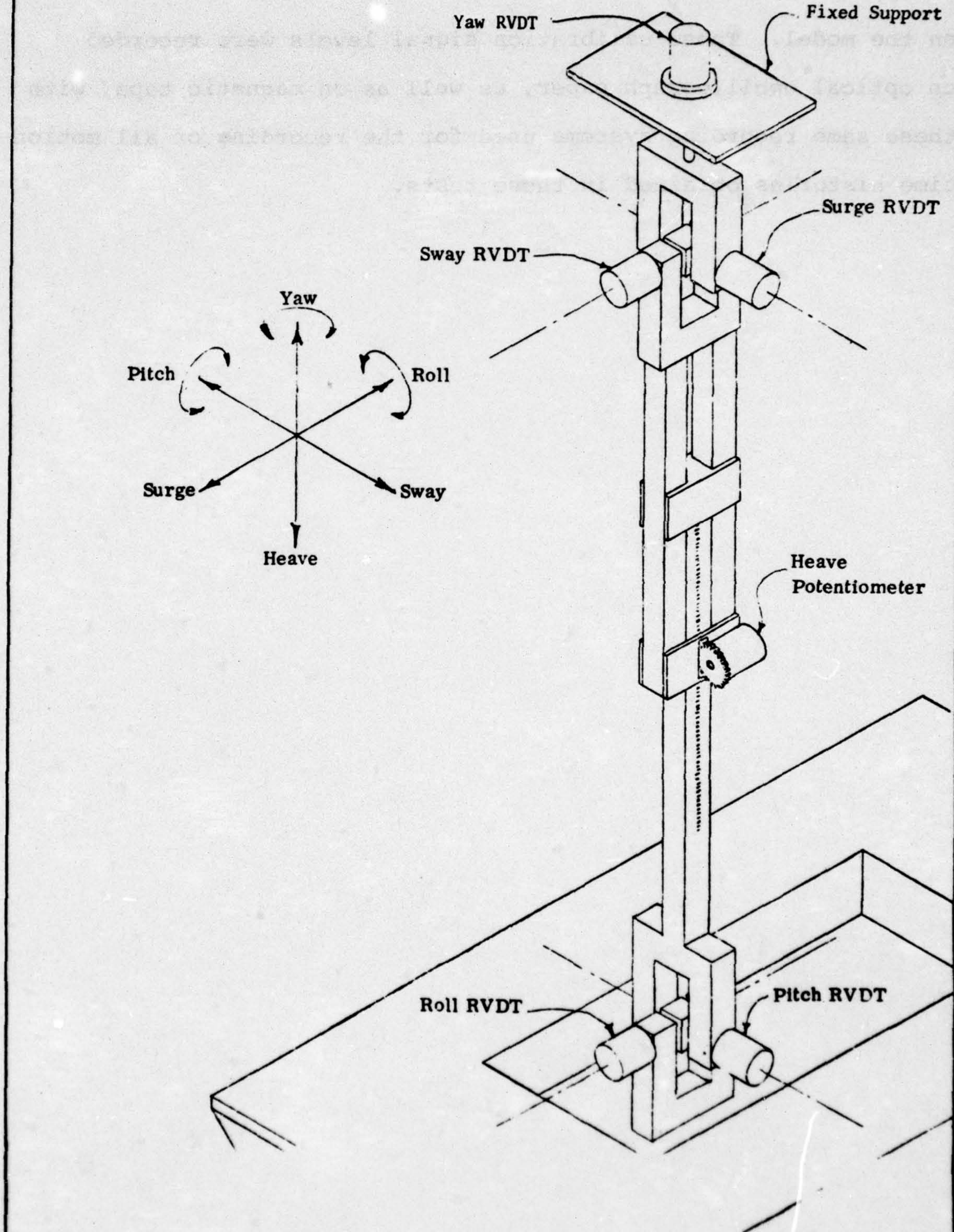

Fig. 1 Motion sensing transducers (MST) at OTC wave tank

on the model. These calibration signal levels were recorded on optical oscillograph paper, as well as on magnetic tape, with these same recording systems used for the recording of all motion time histories obtained in these tests.

6.0 TEST PROGRAM AND CONDITIONS TO BE SIMULATED

The present investigation requires model tests that will simulate the conditions associated with specific accident mechanisms. The tests will involve both boats, loaded symmetrically and asymmetrically, for a range of wave conditions, heading relative to the waves, magnitude of load, and load distribution. These basic loading related accident conditions are to be simulated in the model tank, using the data provided in [1], according to the specifications in [2]. In addition to simulating specified full scale tests wherein accidents occurred, special tests will be performed to determine response amplitude operators (amplitude of motion response divided by wave amplitude) for a series of regular waves, as well as tests to obtain transient motion decay curves for the roll and pitch angular degrees of freedom. The following describes the particular test conditions that were simulated in the model tank tests.

6.1 Accident Mechanism I

Jon boat loaded in waves; the following tests were performed, with identification of the particular model test runs corresponding to those conditions.

(1) Bow to waves

- (a) One passenger load
- (b) Two boat velocities
- (c) One wave spectrum

} Test Run No. 101 & 102

(2) Stern to waves

- (a) One passenger load
- (b) Two boat velocities (one ahead, one astern)
- (c) One wave spectrum

} Test Run No. 103 & 104

(3) Beam to waves

(a) Two passenger loads
(b) One boat velocity (0 speed)
(c) One wave spectrum (for each passenger load)

Test Run No. 105 & 106

6.2 Accident Mechanism II

Jon boat loaded asymmetrically in waves; the following tests were performed, with identification of the particular model test runs corresponding to those conditions.

(1) Bow to waves (boat velocity = 0, boat anchored by bow, represented by a 60 lb. weight)

(a) One passenger load distribution
(b) One wave spectrum

Test Run No. 201 & 202

(2) Stern to waves (boat velocity = 0, boat anchored by stern, represented by a 60 lb. weight)

(a) One passenger load distribution
(b) One wave spectrum

Test Run No. 203 & 204

(3) Beam to waves (boat velocity = 0)

(a) Two passenger load distributions
(b) One wave spectrum

Test Run No. 205 & 206

6.3 Accident Mechanism III

Runabout loaded asymmetrically in waves; tne following tests were performed, with identification of the particular model test runs corresponding to those conditions.

(1) Bow to waves (boat velocity = 0)

(a) One passenger load distribution
(b) One wave spectrum

Test Run No. 301

(2) Stern to waves (boat velocity = 0)

(a) Two mooring configurations (anchored and unanchored)
(1) One passenger load distribution
(2) One wave spectrum

Test Run 302

(3) Beam to waves (boat velocity = 0)

(a) Two passenger load distributions
(b) One wave spectrum

Test Run 303

A listing of all of the various test conditions that satisfy these accident mechanisms, together with the corresponding identification of the Coast Guard load condition and full scale test run, as well as the corresponding model test run at OTC is given in Table 4. The freeboard values, forward and aft, for each of the different load conditions are given in Table 5.

6.4 Angular Decay Curves

Another requirement is to obtain the transient (time history) decay curves for both models, in the angular modes of roll and pitch. These records were obtained before the actual wave response tests, after the model was properly ballasted to correct displacement and inertia. The model was held at some initial angular displacement and released, with the complete angular motion response obtained on oscillograph paper as a function of time. The roll and pitch transient responses for both boats were obtained at the start of each run for a different loading condition of the craft, allowing some correspondence with similar transient responses obtained in the full scale Coast Guard tests [1].

TABLE 4

RELATIONSHIPS BETWEEN TEST CONDITIONS AND TEST PLAN

Test Condition	O.T.C. Test No.	Model*	Speed (kt.)	Wave Spectra C.G. Run No.	Wave Spectra O.T.C. Spectrum No.	Heading*** deg.	C.G. Load Condition No.
I-1	101	JON	0	1	AA	180	1
I-1	102	JON	3	1	AA	180	1
I-2	103	JON	0	2	BB	0	2
I-2	104	JON	3	2	BB	0	2
I-3	105	JON	0	2	BB	90	3 (Tank)
I-3	106	JON	0	2	BB	90	4
	107	JON	3	calm		180	1
II-1	201	JON	0	14	CC	180	14
II-1	202	JON	0	14	CC	180	5**
II-2	203	JON	0	15	DD	0	15
II-2	204	JON	0	15	DD	0	6**
II-3	205	JON	0	14	CC	90	14
II-3	206	JON	0	15	DD	90	15
III-1	301	RUN	0	9	EE	180	9
III-2	302	RUN	0	11	FF	0	11
III-3	303	RUN	0	12	GG	90	9
III-3	304	RUN	0	11	FF	90	11

* JON refers to Jon boat
RUN refers to Runabout

** These conditions have the anchor weight added on <u>after</u> boat was ballasted to specified conditions.

*** The notation used for heading angles is as follows:
180° → head seas
90° → port beam seas
0° → following seas

TABLE 5

MEASURED FULL SCALE

FREEBOARDS FOR LOADING CONDITIONS

Load Condition Number	Boat*	Freeboards, ft. Fwd	Freeboards, ft. Aft
1	JON	0.708	1.083
2 [RAO]	JON	1.167	0.875
3 (Tank)	JON	0.708	1.042
4	JON	0.781	0.750
5 sitting	JON	0.771	1.146
5 kneeling	JON	0.563	1.354
6	JON	2.125	0.354
14	JON	0.542	1.417
15	JON	2.125	0.354
9	RUN	1.250	1.833
11	RUN	3.000	0.833
RAO	RUN	2.180	1.340

* JON refers to Jon boat

RUN refers to Runabout

6.5 Response Amplitude Operator (RAO) Determination

It was required to obtain response amplitude operator (RAO) for the major motions of pitch and heave head seas, and roll and sway in beam seas. The RAO is defined to be the ratio of the amplitude of the response to the amplitude of the oncoming regular wave, at the same frequency. These responses were to be found for two different wave heights for each of five wavelengths, with the particular wave height selected as a fraction of the wavelength. The nominal wave heights selected were $H = \lambda/40$ and $H = \lambda/20$, which allows an assessment of the degree of linearity of the responses.

In addition to the main motions per se, additional measurements in head seas were the relative bow motion (forward freeboard variation), from which a freeboard RAO and phase angle are determined, and for beam seas the relative gunwale motion, from which a gunwale freeboard RAO and phase angle are found. At the same time, if a particular motion is evident and significant during any of these tests, such as e.g. the heave motion in beam seas, that measurement is also obtained and analyzed to find the appropriate RAO data.

The loading conditions for RAO determination for the jon boat corresponds to load condition 2, and for the runabout the loading is specified as "RAO for runabout". Both of these load conditions were generally even loading cases. These regular wave tests for RAO determination for each craft were run for a series of waves whose length were given by the following:

For pitch and heave (head seas)

$$\frac{\lambda}{L} = 0.75,\ 1.0,\ 1.5,\ 2.0,\ 2.5$$

For roll and sway (beam seas)

$$\frac{\lambda}{L} = 0.5,\ 0.75,\ 1.0,\ 1.5,\ 2.0$$

where the representative length L is the LBP for the particular load condition.

6.6 Measurements Required

For all tests runs, information on the model characteristics such as total weight, passenger load distribution, gyradii, etc. was tabulated. The wave characteristics, such as amplitude and wavelength for regular waves and the power spectra of the random waves that are generated in the tests, were also known and time history records obtained on both oscillograph and magnetic tape. Time histories of the craft motions (pitch, heave, roll and sway) as well as local freeboard (at bow, stern or gunwale depending on model orientation during the tests) were also recorded in this same manner.

During the tests, observations of the location of water ingress (if any) were also made. The model was also lined with a grid, of 1 in. vertical spacing, and each test run made was recorded on color motion picture film, allowing a vivid pictorial description of the model motions.

All test data including movies, stills, test log, oscillographs and magnetic tape will be forwarded to the Coast Guard with this report.

7.0 STATE OF THE ART - MODEL TESTING IN WAVES

The use of model testing in waves, in order to predict the motions of a craft in a seaway, is a generally accepted method used in towing tank laboratories throughout the world. The capability of properly simulating motion responses of any vehicle is dependent on satisfying particular similitude relationships which, in the case of craft in waves, is usually satisfied by the use of Froude scaling. This particular method, which involves inertial and gravity effects primarily, is usually sufficient whenever the particular phenomanon being investigated is not significantly dependent upon viscous effects. In the case of ship motion in waves, this is usually satisfied in almost all cases, with the possible exception of roll motion where an appreciable portion of the roll damping is influenced by viscous effects (and possibly surface tension). However, the particular degree of influence of these non-Froude effects is dependent on the relative scale of the model with respect to the prototype craft. The relative degree of variation with Reynolds number and the influence of separated flow around corners, edges, etc. in determining roll damping may not vary to a large degree when the flow field has the same relative behavior, as indicated by the critical values associated with transition from laminar turbulent flow and the occurrence of separated flow (in the present case the large size of model relative to the prototype craft can be expected to generally minimize these effects).

With the modeling requirements satisfied such that Froude scaling considerations are predominant, the motion responses in waves obtained from model tests are good predictions for full scale craft behavior. There are a number of ways of using model test data for prediction of full scale responses, which depend upon the nature of the analysis that is intended for ultimate use. Thus methods of determining ship motion response characteristics in various irregular seas by use of spectral analysis techniques applied to linear systems (motion responses proportional to wave amplitude, for a given wave length) is a readily accepted technique by naval architecture-hydrodynamic test laboratories, as well as a tool for analytic prediction (see [3]). Such techniques are readily applicable to conditions where the wave environment is accurately known in regard to frequency content and direction relative to the craft, so that the model test procedure accurately simulates the full scale craft response in the same basic wave conditions.

While many investigations have been made to determine ship motion characteristics by means of measuring the various rigid body motions of a ship, very limited investigations have been made to determine the occurrence of shipping of water (and also the specific accident conditions that are the subject of the present investigation). Model tests to determine wetness as a function of freeboard and flare were carried out by Newton [4] for relatively fine ships running at significant forward speeds in head seas. This particular investigation determined certain wetness contours that characterize the

degree of wetness, which are associated with the relative bow motion as compared to the available freeboard of the ship. The influence of the freeboard forward on the degree of wetness was shown to be a major factor, indicating that a larger available freeboard would reduce the occurrence of wetness due to water coming over the bow. Increasing flare was shown to be equivalent in an increase in freeboard, which was also a beneficial effect in reducing wetness. This information was then used, together with the probability of occurrence of waves of different height and length characteristics, to determine the relative incidence of wetness during various types of operating conditions represented by speed and sea state. A further discussion of a general technique similar to that approach, based on the use of extensive model test data for ship responses in regular waves, was presented in [5]. This method made use of spectral analysis techniques and statistical properties of a linear motion response, which were then combined with the relative occurrence of different sea conditions in order to predict the probability of occurrence of wetness at the bow of ships of different types. Further studies, which use model test data for analysis of deck wetness was carried out in [6] in order to obtain some degree of correlation with the work of [4].

Since the ships considered in this case had relatively high speed, considerations of the dynamic water elevation at the bow ("swell-up") and the deformation of the waves due to the presence of the advancing ship, etc., were used to predict

the degree of deck wetness. This latter investigation ([6]) serves to indicate the necessity of incorporating consideration of local wave deformation and dynamic effects due to the ship motion, which must be obtained from separate empirical studies, in order to provide an adequate description that would tend to correlate the degree of wetness, since consideration of the relative bow motions alone is not sufficient. However, the procedure does point out the occurrence of effects in model scale, which are primarily dependent on Froude number, and which are expected to be proper simulations of full scale effects.

In all of the investigations described above, which are concerned with determining the degree of wetness of a ship in waves, the particular considerations have been devoted to conventional ships advancing at a relatively large forward speed in various wave systems. None of these investigations deal directly with duplicating a specific accident situation, but only characterize the occurrence of wetness due to the elevation of the local wave system over the bow (i.e. since head sea motions were only considered) due to the relative ship motions at the bow. While no direct experiments on accidents per se (for small boats of the type considered in this investigation) have been carried out in the available published literature, it is expected that model motions with respect to the local wave system are properly simulated by conventional techniques of tank model testing for phenomena that scale in accordance with Froude scaling. Since these relative motions determine the occurrence of shipping water,

it can be projected that adequate simulation of the motions would allow proper modeling of the occurrence of accidents on small boats due to shipping water. This expectation is only based upon the general ability of adequate duplication of the craft motions and the existing wave characteristics, assuming that as the prime environmental disturbance mechanism.

The present investigation is directly intended to establish the feasibility of this approach by model tests of small recreational boats in waves that represent the environment experienced by such craft.

8.0 ESTABLISHMENT OF WAVE ENVIRONMENT, FULL SCALE AND MODEL

In order to successfully reproduce full scale motions with model tests in the laboratory it is necessary to first reproduce the environmental conditions as they existed. More specifically it is necessary to reproduce the same ocean wave environment in the tank that was present during the full scale tests. Since ocean waves are often directionally spread as opposed to being unidirectional, this task becomes very difficult. It is difficult enough to measure directional wave spectra, let alone to reproduce one in a laboratory. The usual approach in engineering studies of vehicle wave dynamics is to assume that the wave environment is unidirectional (long crested) and to represent it as such in the laboratory, which is all that could be accomplished in the OTC tank. This is the approach that was followed here, assuming also that the observed conditions in full scale were unidirectional waves.

8.1 Full Scale Wave Measurement

The wave elevation time histories were measured by the Coast Guard at locations nearby the test area. The records were written out on strip charts and as such had to be analyzed by hand. They were indicated by a series of points, obtained every 0.25 sec., and displayed on paper with a maximum height of about 0.25 in. in most cases, with much of the waves less than that and a smaller amount ranging up to larger elevations of about 0.5 in. This process proved to be extremely time consuming and required an inordinate amount of labor. To reduce this effort to a more manageable level it was decided to take the wave record for an

entire series of runs (same day, same location) to be represented by the wave record measured for one run during that sequence. This simplication should be valid because of the relatively short time span over which a test series was conducted (or the order of 2 hours). This simplication was checked by analyzing two wave records from the same full scale test series (Runs 9 and 12). The spectra for these two runs are shown in Figures A.1 and A.2 (along with the model tank representation which will be discussed later). The time between these two runs was approximately 15-20 minutes. Examination of the spectra shows that both have approximately the same energy content and very nearly the same rms wave amplitude (i.e. σ_η = 1.15 ft. for Run 9 and σ_η = 1.03 for Run 12). While this one check does not prove that this simplification is valid for all cases, it does show that the wave environment was reasonably stationary for the test series considered. In any event, if the wave system is not stationary, than the entire procedure for statistical analysis used here (and just about everywhere in wave and ship interaction analyses) is not applicable. It is therefore necessary and convenient to assume stationarity.

8.2 Generation of Model Wave Spectra

The system used at OTC to generate random seas is to sum component sine waves with appropriate amplitudes, as indicated previously. Nine wave systems were chosen for simulation at OTC. The correspondence between Coast Guard run numbers and OTC designations are shown in Table 6. Also shown in Table 6 are the rms of both the full scale measured waves as well as

TABLE 6

COMPARISON OF RMS AMPLITUDES OF WAVES

OTC Wave Designation	Coast Guard Designation	Full Scale	Measured in Tank	Notes
AA	1	.151	.13	
BB	2	.180	.18	
CC	14	.267	.16	Truncated
DD	15	.139	.12	
EE	9	1.152	.49	Truncated
FF	11	.191	.26	Truncated
GG	12	1.03	.46	Truncated

the rms of the waves created in the tank. There were only significant differences in rms for the runs where truncation was necessary.

In some instances considerable wave energy was concentrated in the region below 1 rad./sec. These frequencies corresponds with wave lengths of 200 feet and above. Since the facility at OTC is not capable of generating scaled waves corresponding to this length (and waves of this length do not influence the motions of the boats considered in this study) it was decided to truncate the spectra (for model simulation purposes) at 1.2 rad./sec. at the low frequency end. Similarly this condition corresponds to the upper end of the wave period, to be considered, i.e. 5 sec., as shown in section 2.0.

Figures A.1 through A.7 in Appendix A show comparisons between full scale measured wave spectra and the simulated wave spectra generated and measured by OTC, some of which reflect the low frequency truncation discussed above. In all cases of the simulated wave spectra, the test duration was of sufficient length to insure a minimum of 100 wave encounters for analysis.

The simulation of the Run 1 spectrum (AA), shown in Figure A.3, was quite good over the range of 1 to 3 rad./sec. For the frequency range over 3 rad./sec. the agreement is not very good, but this is approaching the low period end, 2 sec., of the specified conditions. Figure A.4 shows the comparison between the Run 2 measured spectrum and the simulation by OTC (BB). The agreement between the two spectra is reasonably good. Figure A.5

shows the comparison between Run 14 and OTC spectrum CC. As can be seen the Run 14 spectrum has most of its energy below 1 rad./sec. The CC spectrum matches the Run 14 spectrum well, only over the range from 1.75 rad./sec. to 3.5 rad./sec., due to the imposed truncation. Figure A.6 shows the match between the Run 15 spectrum and OTC spectrum DD. The agreement here is good over the range of frequencies from 1 rad./sec. to 3 rad./sec. Similar comparisons are shown in Figures A.7, A.1 and A.2 for the rest of the combinations in Table 6.

It should be pointed out that while the spectral simulations shown here are in general satisfactory, they could probably have been improved by increasing the number of component waves used by OTC to generate the spectra. Hence the first step in the model testing program has been successfully achieved, which by itself does not completely assure successful correlation between the full scale and model tests in regard to craft responses.

8.3 Measurement of Power Spectra

All spectra obtained in the course of this work were computed via the autocorrelation approach to spectrum analysis. This procedure relates the Fourier transform of the auto-covariance function to the energy density function of a random process. While this method of spectral analysis is fast being replaced by the faster and more direct method (of computing Fourier coefficients via the Fast Fourier Transform (FF) and computing the power spectrum from the sums of the square of the coefficients) the autocorrelation approach is used in this study.

Since we are concerned with boat motions, which are known a priori to be relatively smooth functions of frequency, it is not necessary to evaluate spectra for a closely spaced grid of frequencies. In addition it can be shown [7] that the wider the frequency band over which the spectrum is estimated, the greater the statistical confidence in the estimate.

It is for the above reasons, along with the fact that Oceanics has an operational computer program and greater experience using the autocorrelation approach, that resulted in the use of this approach.

8.3.1 Theoretical Foundation

It can be shown that in the limit as the record length goes to infinity the cosine Fourier transform of the autocovariance function becomes proportional to the true energy density function.

For a random variable $x(t)$ we can write:

$$R(\tau) = \frac{1}{T} \int_{0}^{T} x(t)\, x(t+\tau)\, dt \qquad (1)$$

τ = lag value

$R(\tau)$ = autocovariance function.

The energy density function is approximated by:

$$S_x(\omega) = \frac{2}{\pi} \int_{0}^{T} R(\tau) \cos\omega\tau \, d\tau \qquad (2)$$

The true energy density function of the process $x(\tau)$ is given by computing the Fourier coefficients of $x(\tau)$ assuming it is periodic and has a period T. The spectrum at the m^{th} frequency is related to the amplitudes of the sine and cosine terms in the Fourier series at the m^{th} harmonic by:

$$S_m = \frac{1}{2} (a_m{}^2 + b_m{}^2) \tag{3}$$

The function $S_x(\omega)$ approaches the true energy density function as the record length T approaches infinity.

8.3.2 Random Sea Data

All data analyzed in this project was digitized for computer analysis. Time histories of waves for the full scale tests were punched on computer cards. Motions and waves (for both the model and full scale tests) were digitized and stored on magnetic tapes. The digitization time interval was chosen to be at most 1/2 the period of the highest frequency present in the data. This choice of sample rate assures that there will be no aliasing of the data. The actual digitization rates were different, depending on what data was being analyzed. For the full scale wave records provided by the Coast Guard the sample rate was .5 sec. The motion data provided by the Coast Guard was sampled every .4 sec. The data generated by OTC was sampled every .316 seconds (full scale). Each sample rate was sufficiently rapid to insure no aliasing of the data occurs. The number of lags in the autocorrelation approach for each case was

selected so that the frequency resolution was for all practical purposes identical.

8.3.3 Computation of Spectra

The spectra were computed using a spectral analysis program written for a CDC 6000 type computer. The program automatically subtracts the mean from the data, computes the variance and corrects the data for instrumentation drift. This program also has the capability of evaluation cross-spectra as well as complex transfer function determinations.

Due to the fact that the data was digitized and analyzed digitally, certain inaccuracies are introduced into the computation of the spectrum [4]. These inaccuracies can be reduced by smoothing either the raw spectrum or the auto-covariance function, which reduce to the same effect. The program used to compute all the spectra for this study accomplishes this by using "hamming" [7]. All this really means is that a moving weighted average of the spectrum replaces the "raw" spectral estimate.

The program must be told the number of "lags" (i.e. number of values of τ, as defined following Equation (1)) that are to be computed. The number of lags along with the digitization rate determines the frequency resolution of the computer spectrum, as shown by

$$\Delta\omega = \frac{\pi}{m_{lags}\Delta t} \tag{4}$$

where m = number of lags

For all spectra computed in this study $\Delta\omega$ was kept at $\simeq .314$ rad./sec. The significance of this is that each computed spectral point is an average over a band $\pi/10$ rad./sec. wide. This frequency band should allow good resolution of the boat response characteristics.

8.3.4 Statistical Confidence

In discussing the accuracy of power spectral estimates, two types of error need be examined. These are:

(1) Errors introduced by sampling and the computational procedure.

(2) Errors introduced by the actual measuring device.

The first type of error is easily determined by the following formula (see [9])

$$\varepsilon = \sqrt{m/N} \tag{5}$$

ε = normalized standard error

m = number of lags

N = number of data points

Values of ε, m and N are tabulated in Appendix E for all the spectral determinations performed during the course of this work. The total extent of each run may be determined by multiplying the number of samples (N) by Δt (also given in the tables in Appendix E).

The second type of error introduces a further degree of uncertainty into our spectral estimates. Any measurement

device has a range of accuracy. This range becomes more important, for spectral determinations, in regions of the spectrum where the energy is low. The percentage error in the spectral estimates in regions of small spectral energy therefore is increased to a greater degree than estimates where the spectral energy is relatively large.

8.3.5 Computation of Transfer Functions

For a motion variable $x(t)$ in a random seaway $\eta(t)$ $S_x(\omega)$ is the response amplitude spectrum of the motion x and $S_\eta(\omega)$ is the wave energy spectrum. From linear theory [3] we have:

$$\left|T_x(\omega)\right| = \sqrt{S_x(\omega)/S_\eta(\omega)} \tag{6}$$

where $\left|T_x(\omega)\right|$ is the magnitude of the transfer function of x. In principle this division is straightforward, but in practice we must keep in mind that frequencies at which the spectral energy is low give rise to large error bands in the spectral estimate. Therefore the division indicated by Equation (6) can be carried out meaningfully only at frequencies where the wave spectrum $S_\eta(\omega)$ has significant energy. As a rule of thumb we take this to be the region where S_η is larger than 10% of its maximum value. As such, in using random sea data to measure transfer functions, it is important to try to find a random sea with its energy concentrated in the band of interest for transfer function determination. In the

present investigation, the magnitude of the transfer function indicated above is also known as the Response Amplitude Operator (RAO).

9.0 COMPARISON OF MODEL AND FULL SCALE ROLL AND PITCH DECAY CURVES

Pitch and roll transient decay curves were generated and recorded for both the full scale boats and the models. The amplitudes, normalized by the initial amplitude, are shown in Figures B.1 through B.18 in Appendix B plotted versus periods of oscillation. Each figure is for an identically ballasted condition between model and full scale. There appears to be reasonable agreement between model and full scale results with perhaps less scatter in the model tests. This should be expected as the ambient conditions for model testing are expected to better approximate calm water than in full scale, and also due to the better control of imposing the initial angular displacement in the model tests.

The period of oscillation (full scale equivalent) are also noted on each figure, and they agreed reasonably well between model and full scale results, having less than 10% difference. In view of the difficulty in obtaining reasonable pitch decay curves, due to the larger relative damping as compared to the case of roll motion, the general agreement here indicates good correlation between model and full scale results in regard to the transient decay aspects of roll and pitch.

10.0 PREDICTIONS OF MODEL PERFORMANCE USING RESPONSE AMPLITUDE OPERATORS OBTAINED FROM REGULAR WAVE TESTS

The feasibility of using response amplitude operators (RAO's) obtained from regular wave tests in predicting model performance depend, on the validity of the principle of linear superposition. If linear behavior is valid, then a response amplitude operator (which is the amplitude of motion divided by the amplitude of the oncoming regular wave) should be independent of wave amplitude. To ascertain the linear qualities of the jon boat and the runabout the regular wave tests were performed at two different relative wave height; viz. a waveheight of 1/40 of each tested wavelength and a wave of twice that magnitude or 1/20 of each tested wavelength, which is considered to be a large wave. Figures C.1 through C.14 in Appendix C show RAO's for both of these waveheights. If the boats were linear in their motion response, then the data points would coalesce, but as can be seen, they do not. In all but one case (roll of jon boat in beam sea for $\lambda/L = .5$) the RAO for the larger wave height is smaller, which is the normal tendency for nonlinear behavior. In addition to the magnitudes of the response operators, the data for the phase angle, of all responses, measured in the RAO tests are presented in tabular form at the end of Appendix C.

If a motion was linear, then the spectrum of this motion would be the same as the square of its RAO times the spectrum of the irregular wave. Assuming the motions are linear, then by dividing the response amplitude spectrum from the irregular

sea tests by the corresponding wave spectrum would give predicted RAO's. The results of this process are also shown in Figures C.1 through C.26, which consider particular load conditions that were not the same as those for which the RAO's were, found in the regular wave model tests. The overlap in wavelength between the regular wave and irregular wave tests was limited by the particular wave spectra determined from full scale tests. In these tests, the energy of the waves was largely at longer wavelengths than is normally used in determining RAO's, which ranges from half the shiplength to about twice the shiplength. The energy content of the wave spectrum was only of sufficient magnitude down to about 1.5 times the shiplength for accurate determination of a predicted RAO by the above process. However, in the range of wavelengths where there is overlap the predicted RAO's agree reasonably well with the RAO's from the regular wave tests. For the longer wavelengths, towards the peaks of the measured wave spectra, nonlinear effects will tend to diminish and the motions of the boats will tend to behave the same as a wave particle with the result that heave and sway amplitudes will approach the wave amplitude, roll and pitch amplitudes will approach the wave slope, and freeboard (relative motion) will approach zero.

As a result of this comparison, it can be seen that RAO's derived from regular wave tests can be applied to the particular seas that the full scale jon boat and runabout encountered, for load conditions that are similar to the tested RAO conditions,

such as symmetric load conditions, for an RAO obtained from tests with a symmetric loading, etc. However less success would be expected for conditions with spectra whose main energy content occurred at wavelengths more in the range of the shiplength because of nonlinear effects that could occur there, depending on the total energy in the waves.

11.0 COMPARISON OF FULL SCALE AND MODEL MOTIONS

Ideally, to compare full scale and model motions it would be necessary to exactly reproduce, in the laboratory environment, the exact conditions encountered in open water by the full scale boat. Since that is not precisely possible, it is nevertheless still possible to reproduce the conditions in a spectral sense (this has been discussed in more detail in a preceding section of this report). It then becomes possible to make a comparison in the spectral rather than the time domain. Unfortunately the reproduction of measured spectra is not exact, which could lead to erroneous conclusions if motion spectra per se are directly compared. Therefore it appears that the best possible comparison to make between full scale and model motions is on the basis of comparing the RAO values in each case.

11.1 Theoretical Basis

The RAO of a random variable x is defined as the square root of the ratio of the power spectrum of x to the power spectrum of the input wave system. Mathematically we have, with

$S_\eta(\omega)$ = power spectrum of the input waves.

$S_x(\omega)$ = power spectrum of the motion x.

$|T_x(\omega)|$ = the RAO of the variable x.

the relation

$$S_x(\omega) = |T_x(\omega)|^2 \, S_\eta(\omega) \tag{7}$$

or alternatively

$$T_x(\omega) = \sqrt{S_x(\omega)/S_\eta(\omega)} \tag{8}$$

which was also given in Equation (6). Theoretically any difference in the wave system should be properly accounted for by this division process. It should be noted though, that Equations (7) and (8) derive from linear theory, e.g. [3], and as such must be used with caution when considering any nonlinear problem. We must be certain that the wave amplitude characteristics are preserved (approximately) in going from the actual open water environment to a laboratory wave tank. An example of this calculation is shown in Figure 2.

11.2 Comparison of Results

Table 7 summarizes all the runs that were compared during the course of this study. There were 13 model test (OTC) runs that simulated actual full scale conditions, as established by the Coast Guard. For head and following sea runs, comparisons are made for heave acceleration and pitch angle. For beam sea run comparisons are made for sway acceleration, heave accleration and roll angle. All OTC measurements were manipulated so as to give the appropriate readings at a location that corresponded with the location of the instrument package on the full scale boats. It should be noted that the tests at OTC measured heave and sway displacement, while the full scale Coast Guard tests measured heave and sway accelerations. The model test translatory motion measurements were converted to accelerations by the following

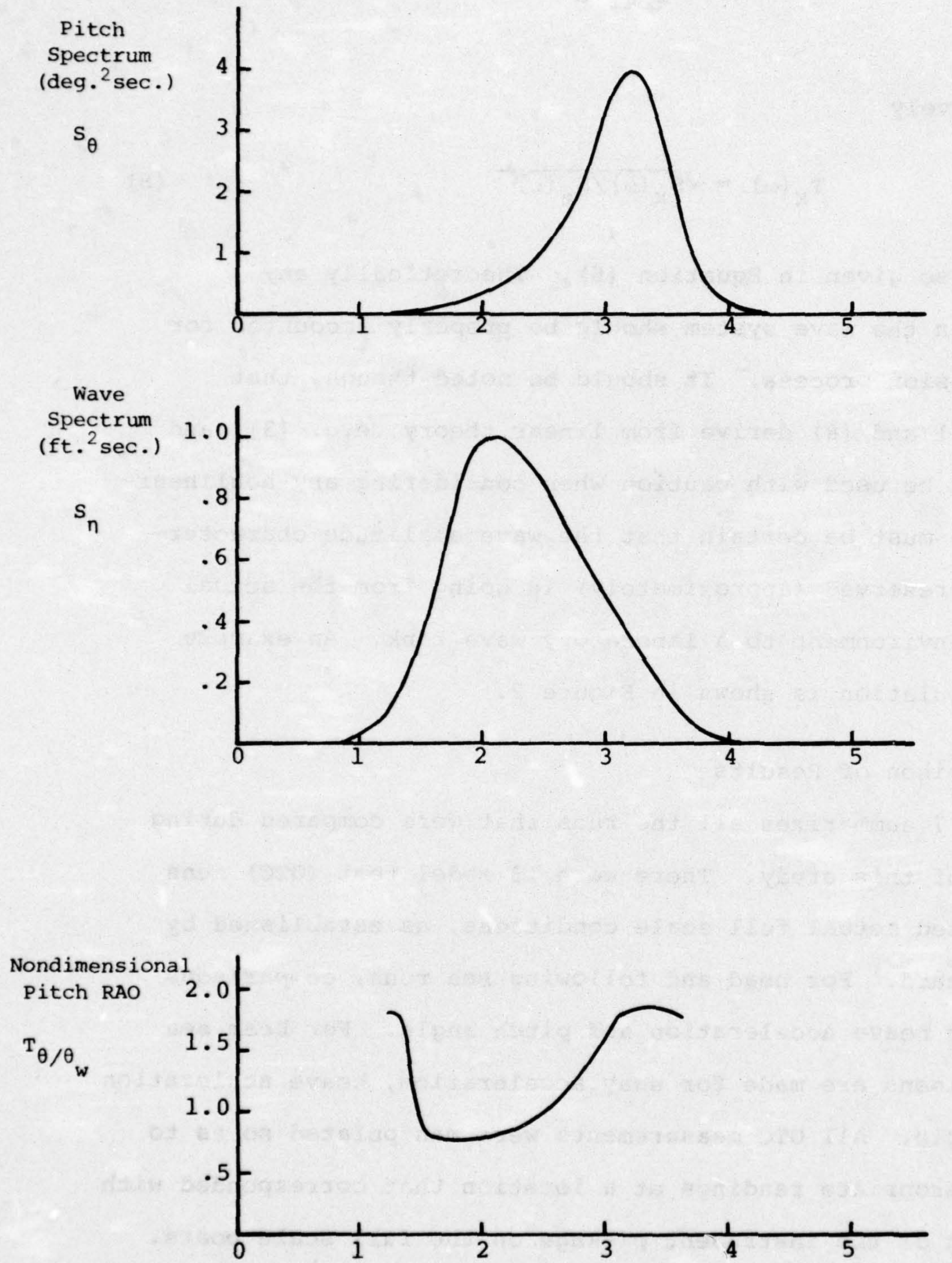

Fig. 2 Example of calculation of transfer functions.

TABLE 7

DESCRIPTION OF TEST RUNS COMPARED BY SPECTRAL - RAO METHODS

OTC Run No.	Coast Guard Run No.	Load	Boat	Heading
101	1	Even	Jon	Head
103	2	Even	Jon	Following
105	3	Even	Jon	Beam
106	4	Over	Jon	Beam
202	5	Bow	Jon	Head
204	6	Stern	Jon	Following
205	7	Bow	Jon	Beam
206	8	Stern	Jon	Beam
301	9	Bow	Runabout	Head
302	11	Stern	Runabout	Following
303	12	Bow	Runabout	Beam
304	13	Stern	Runabout	Beam
201	14	Bow	Jon	Head
203	15	Stern	Jon	Following

relations:

$$T_{\ddot{z}}(\omega) = \omega^2 T_z(\omega) \tag{9}$$

for heave acceleration, and

$$T_{\ddot{y}}(\omega) = \omega^2 T_y(\omega) \tag{10}$$

for sway acceleration.

Figures D.1 through D.34 in Appendix D show the comparisons of the full scale and the tank random sea runs. The RAO's for the pitch and roll angles are nondimensionalized by the wave slope. The acceleration RAO's are in units of (g's/ft.). In order to assess the degree of comparison between tank modelling and full scale tests, and to illiminate common causes of either good or poor agreement, each comparison is rated. The rating can either be good, fair or poor. An example of a good comparison is Figure D.27; fair comparison is Figure D.18; and poor comparison is Figure D.29. A tabulation of these ratings versus type of boat, loading, response or heading might then be beneficial in determining base reasons for the agreement or lack of it.

The tabulations shown in Table 8 show overall better agreement for the runabout than the jon boat. The heave accleration had the best agreement among the responses. No trend could be discerned with regard to loading or heading. Overall the agreement is fair to good in 80% of the comparisons. While there is definite room for improvement, obtaining this degree

TABLE 8

TABULATIONS OF AGREEMENT BETWEEN

FULL SCALE AND TANK TESTS

	Jon Boat			Runabout		
	Good	Fair	Poor	Good	Fair	Poor
Overall	2	16	6	6	3	1
Response						
Heave	1	9	0	4	0	0
Sway	1	2	1	1	1	0
Pitch	0	3	3	1	1	0
Roll	0	2	2	0	1	1
Load						
Even	1	5	1	-	-	-
Overload	0	2	1	-	-	-
Bow	0	3	2	3	2	0
Bow and Anchor	0	1	1	-	-	-
Stern	1	3	1	3	1	1
Stern and Anchor	0	2	0	-	-	-
Heading						
Head	0	4	2	1	1	0
Following	0	5	1	2	0	0
Beam	2	7	3	3	2	1

of correlation should be considered as acceptable.

11.3 Difficulties in Measuring and Analyzing Full Scale Motions

It is worthwhile at this point to discuss some of the problems associated with trying to measure and analyze boat motions (especially small boat motions) in open water. These difficulties are listed below.

1) Ocean wave spectra are seldom unidirectional, yet we must treat them as such. This influences both the spectral simulation and the choice of heading, i.e. beam, head or following seas. It is known that the measured motions are all sensitive to heading, so that improper knowledge of wave directions would affect the results.
2) In order to maintain a given orientation with respect to the waves, lines must be attached to the boats at various points. These lines may have an influence on boat motions.
3) It is very difficult and often not possible to keep a fixed orientation of the boat with respect to the waves in the presence of wind and current.
4) In the full scale tests, human loads were actually present, while in the model tests dead weight was used to simulate the loads. These different types of weight have different characteristics that may influence the motions.

5) During most of the full scale tests conducted by the Coast Guard, appreciable wind was reported. The effect of the wind, including gusts, on the light flat-bottomed boats analyzed here could be of the same order in lateral acceleration as the wave induced acceleration (a 4 kt. gust could induce about .03 g's).

11.4 Summary and Interpretation of Comparison

Comparisons have been made between 13 full scale runs made by the Coast Guard and the corresponding runs made in the model tests. In general, the results of the comparison can be termed "good" to "reasonable". The difficulties associated with measuring boat motions in open water have been described above. Taking into account the numerous difficulties that are encountered in full scale tests, and the dependence on requirements of linearity of responses, the agreement between the two sets of data could be termed quite satisfactory. This does not mean that there are no difficulties in understanding model tests, since it was difficult in some of the conditions tested to establish the correct inertia (while sufficiently close matching of model dimensions and weight were achieved). The effects of this inertia difference were not found to be important since the natural frequencies of model and full scale craft (which craft inertia affects significantly) did not differ by much. Furthermore then natural frequencies were outside the specified range of frequencies for the waves, as discussed previously. In any event it is apparent that the tank tests present a more controlled method for evaluating the overall trends in performance of small boats. Any further improvement

in correlation between full scale tank tests would require better control over the full scale test environment and arrangements for measurement. This is not to say that there is no room for improvement in the tank modeling procedure used at OTC.

12.0 COMPARISON OF WATER SHIPPED AND SWAMPING BETWEEN FULL SCALE AND MODEL TESTS

A comparison was made between water shipped and occurrences of swamping between full scale and model tests, and is summarized in Table 9. The results shown there do not indicate any correlation between full scale and model test results. It has been shown elsewhere in this report that there was reasonable agreement between model and full scale motions. With this in mind, it is difficult to explain such poor agreement in swamping and shipping of water, but some thoughts do come to mind.

The character of the wave may be different in a tank from that encountered on Long Island Sound. It is expected that in these areas waves do tend to be choppy, i.e. more peaked, which could be associated with the wind effects. Also, the wave directional properties of the real environment might be important, so that combined motions are present in full scale which are not simulated in the model tests with unidirectional waves. As an illustration, the relative freeboard variation (at the stern, port or starboard side) in oblique waves would include roll effects that could produce motions that might result in shipping water that would not be present in unidirectional waves (head or following seas). Lastly, the full scale wave spectra bandwidths were widely removed from the resonant periods of the boats in heave, pitch and roll, which ranged from 1.2 - 1.8 sec.. This resulted in poor matching of the energy content of the waves in the neighborhood of such frequencies with the wave spectrum generated in the tank. Thus, even though both the full scale and

TABLE 9

WATER SHIPPED DURING MODEL AND FULL SCALE TESTS

Coast Guard Test No.	Test No.	Full Scale Results	Model Results
1	101	swamped	none
4	106	swamped	none
6	204	swamped	none
7	205	took on water	none
8	206	swamped	none
9	301	took on water	none
11	302	swamped	3 qts. (model scale)
12	303	took on water	none
13	304	took on water	none
14	201	swamped	none
15	203	swamped	none

tank spectra were small in this range of frequencies, the magnitude of the spectra might be critical when viewed in terms of the possible amplification by the heave and pitch transfer functions.

Since in our opinion, this situation was brought about by the Coast Guard specified range of wave periods, and the difficulty in obtaining accurate spectral representation of the full scale waves in the higher frequency range due to the method of obtaining the full scale wave measurement and reading them accurately, a better method of wave measurement and recording of such data should be accomplished for any future work. The spectral resolution in the higher frequency range would not have been increased by increasing the sampling rates (which was adequate for the spectral evaluation, as carried out here) since the number of lags would also have to be increased to retain the same frequency resolution and would also result in the same degree of relative error (see Equation (4) and (5)).

13.0 CONCLUSIONS AND RECOMMENDATIONS

13.1 Conclusions

As a result of the present investigation, a number of conclusions relating to modeling recreational boat accidents via tank testing have been obtained. These various conclusions are listed below:

1. It is generally possible to represent, in model scale, the spectrum of the waves that were determined from analyzing full scale wave records. However the degree of matching in the high frequency region may be affected by the poor data measurements in full scale for this range, thereby limiting the ability to duplicate the effects of the actual full scale waves.
2. The comparison of the transient decay curves for roll and pitch, model and full scale, when based upon normalizing the results relative to the initial angular displacement, shows good agreement in most cases. The magnitude of the different period, as well as the nature of the curves themselves, show sufficiently good agreement in spite of difficulties associated with obtaining suitable initial conditions for transient responses in full scale open water conditions.
3. It is possible to use RAO values obtained from regular waves to predict model performance in irregular seas, as long as the RAO values were obtained for similar loading conditions of the craft (and of course the same

heading). However this will depend upon the energy content of the waves, since a wave system having energy concentrated in the region of the boat natural periods may not produce such good agreement due to possible nonlinear effects in that region.

4. The comparison of model and full scale motions in random waves, on the basis of determining the motion RAO by means of spectral analysis methods, shows agreement that ranges from good to reasonable. However, the comparison is affected by the influence of the directionality of waves, which is not known precisely, as well as the effect of local wind, including gusts.
5. The comparison between the incidence of shipping water and/or swamping between the model tests and full scale conditions was very poor. This aspect is probably also influenced by the wave directional properties, wind effects, and the lack of proper reprsentation of wave energy in the region of boat motion resonances (due to the truncation of the wave spectra).
6. The feasibility of tank modeling of full scale accidents has not been fully established by the present investigation. The different contributing causes lending to this result have varying degrees of influence (as described when discussing wave frequency bandwidth limits; accuracy of determining full scale wave amplitudes which are then represented in model scale;

influence of wave directionality, etc.), which require further testing to overcome such problems that were discovered in the present study. Nevertheless, the ability to match a large proportion of the various measured motions provides a basis for expecting improved modeling capability when the limiting factors described above have been corrected.

13.2 Recommendations

Based upon the above results, and the discussion of various features that contribute to the observed and deduced findings of this study, a number of recommendations are made. These are listed below by the following:

1. Improved wave measurement should be made in full scale, using electronic recording, preferably in digital form on magnetic tape. The sampling rate presently used for the full scale wave measurements would be adequate to cover the frequency range of interest. The waves should be analyzed, with accurate measurements obtained for that purpose, in a range of frequencies that encompass the boat motion natural resonance periods, which should extend down to about 1 sec. at the low end of the period range. The more suitable range of periods would then be from 1-4 sec., rather than the originally specified range. This range of wave periods should then be used in a further model test program to enlarge the coverage of conditions that would be

available to compare to the full scale motions measurements (and observed shipping of water).

2. The possibility of extending the full scale wave measurement, in a more sophisticated form by means of an array of sensors, should be considered in order to obtain information on the directional aspects of the wave spectrum.
3. If directional information is available, and such effects are found to be significant, then assessment of motions would have to use theoretical methods (for conditions not measured in any model tests in unidirectional waves) to provide procedures for predicting craft motions and incidence of shipping water. Further model tests would then be required to establish the validity of the computational tools for this purpose, with the boat model held restrained at various intermediate headings in order to allow establishment of the basic responses as a function of more heading angles.
4. Measurements of the wind should also be made in the local region of the boat during full scale tests, for both magnitude and direction, with continuous recording. A separate analysis should be made of the possible wind effect on craft motions, allowing for gusts superimposed on a steady wind, in order to assess the possible degree of error, or extent of influence, on the motions induced by wind.

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APPENDIX A

COMPARISON OF WAVE SPECTRA, FULL SCALE AND MODEL

APPENDIX A

		Test No.
1.	Comparison of wave spectra, full scale and model	9
2.	Comparison of wave spectra, full scale and model	12
3.	Comparison of wave spectra, full scale and model	1
4.	Comparison of wave spectra, full scale and model	2
5.	Comparison of wave spectra, full scale and model	14
6.	Comparison of wave spectra, full scale and model	15
7.	Comparison of wave spectra, full scale and model	11

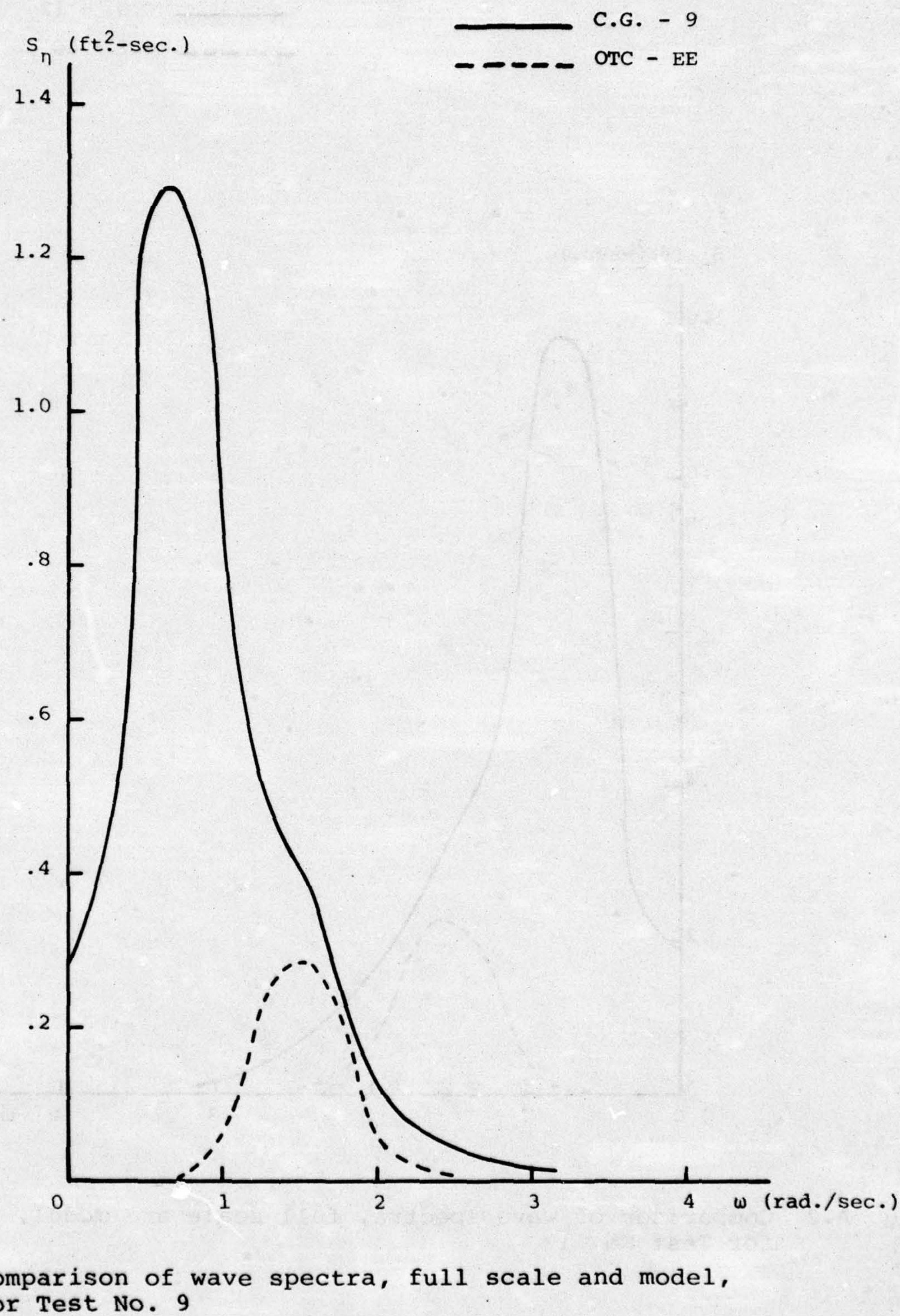

Fig. A.1 Comparison of wave spectra, full scale and model, for Test No. 9

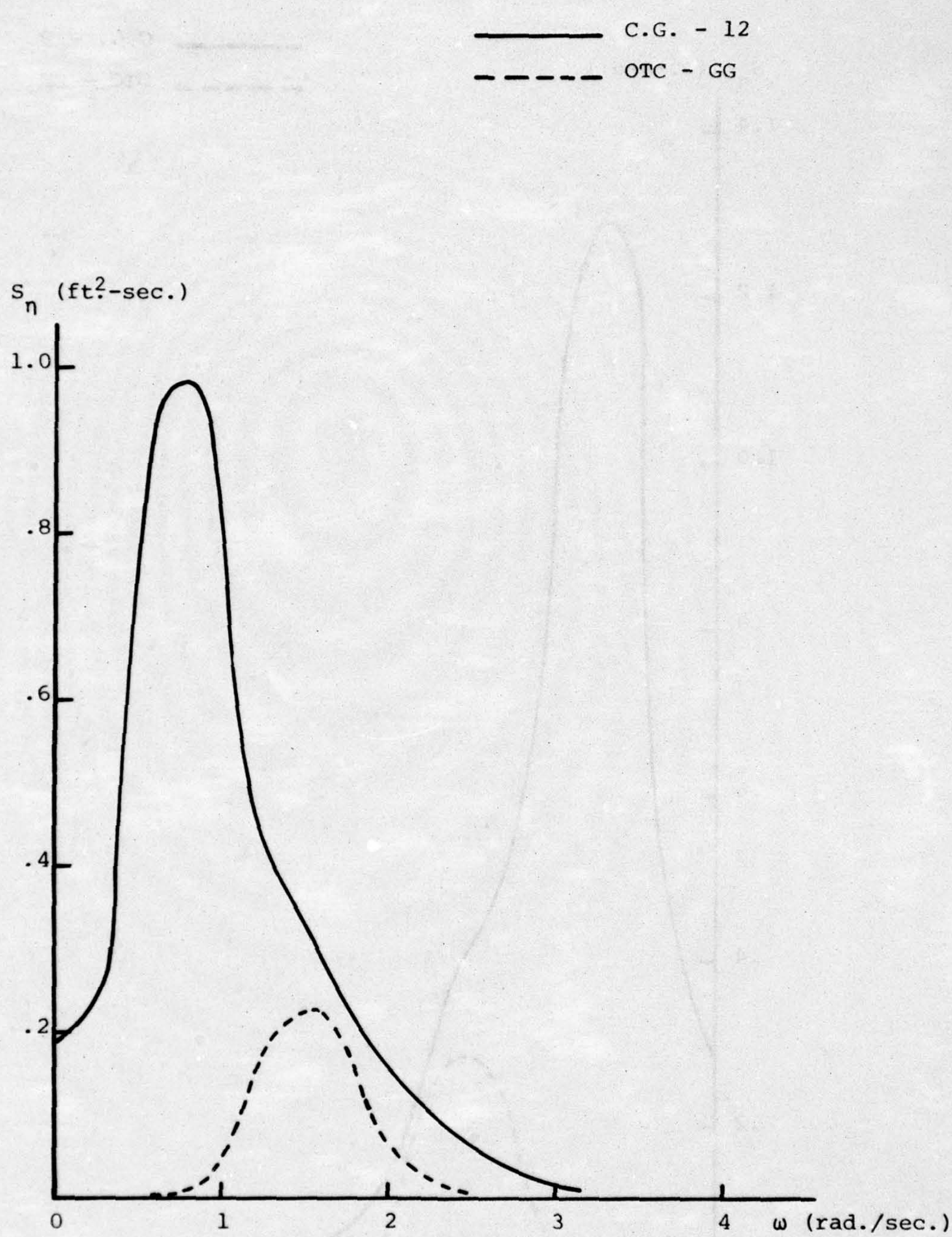

Fig. A.2 Comparison of wave spectra, full scale and model, for Test No. 12

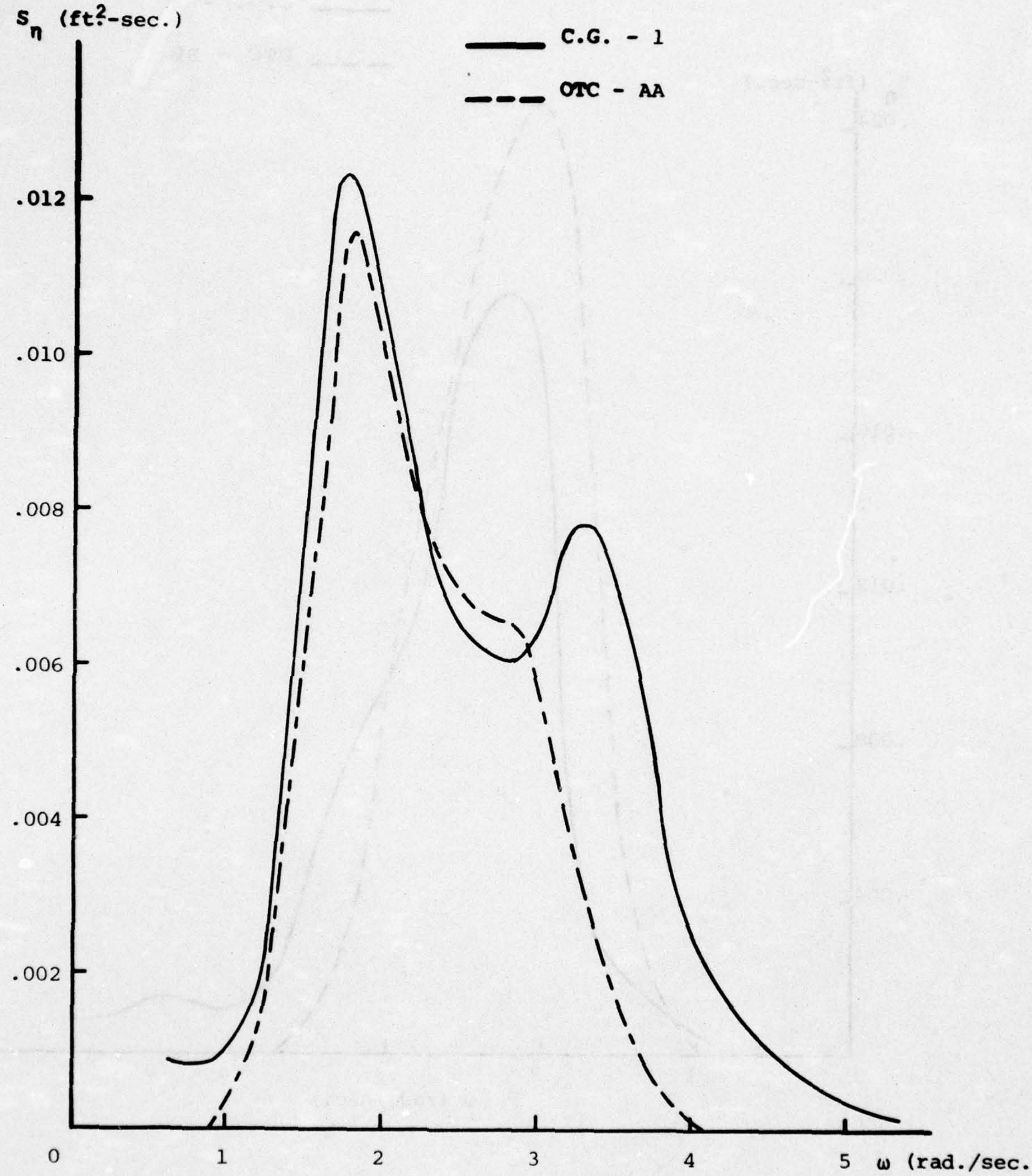

Fig. A.3 Comparison of wave spectra, full scale and model, for Test No. 1

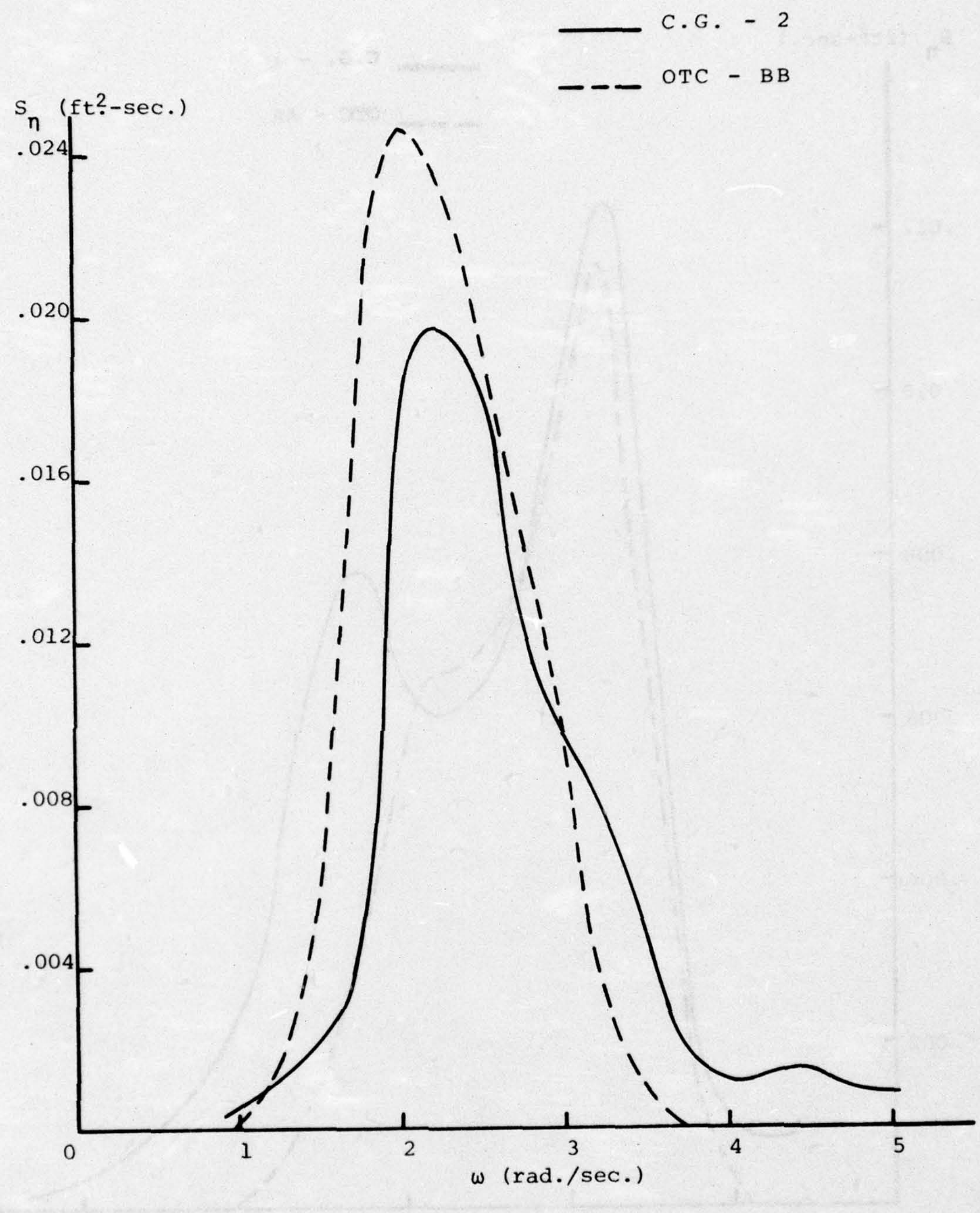

Fig. A.4 Comparison of wave spectra, full scale and model, for Test No. 2

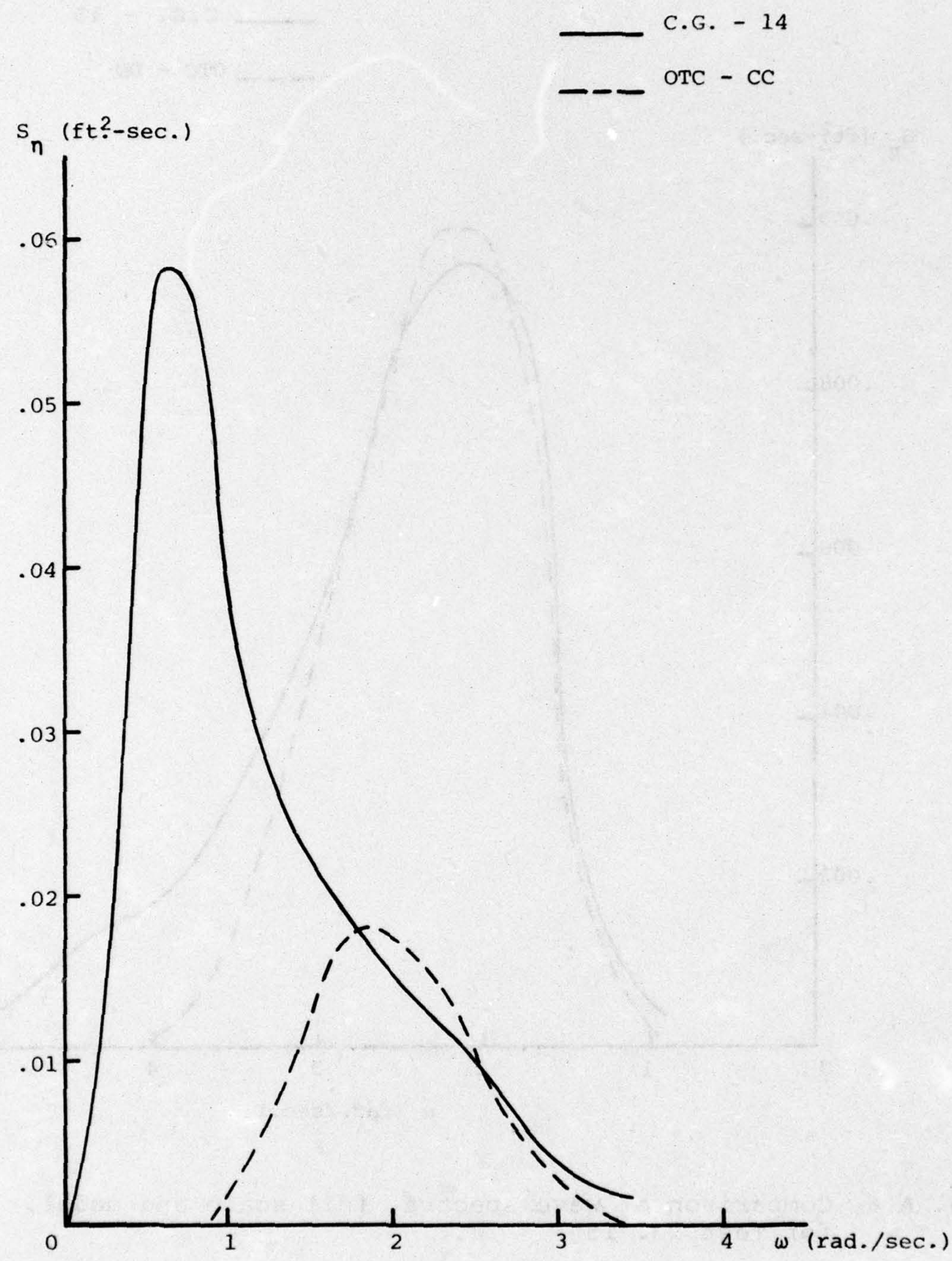

Fig. A.5 Comparison of wave spectra, full scale and model, for Test No. 14

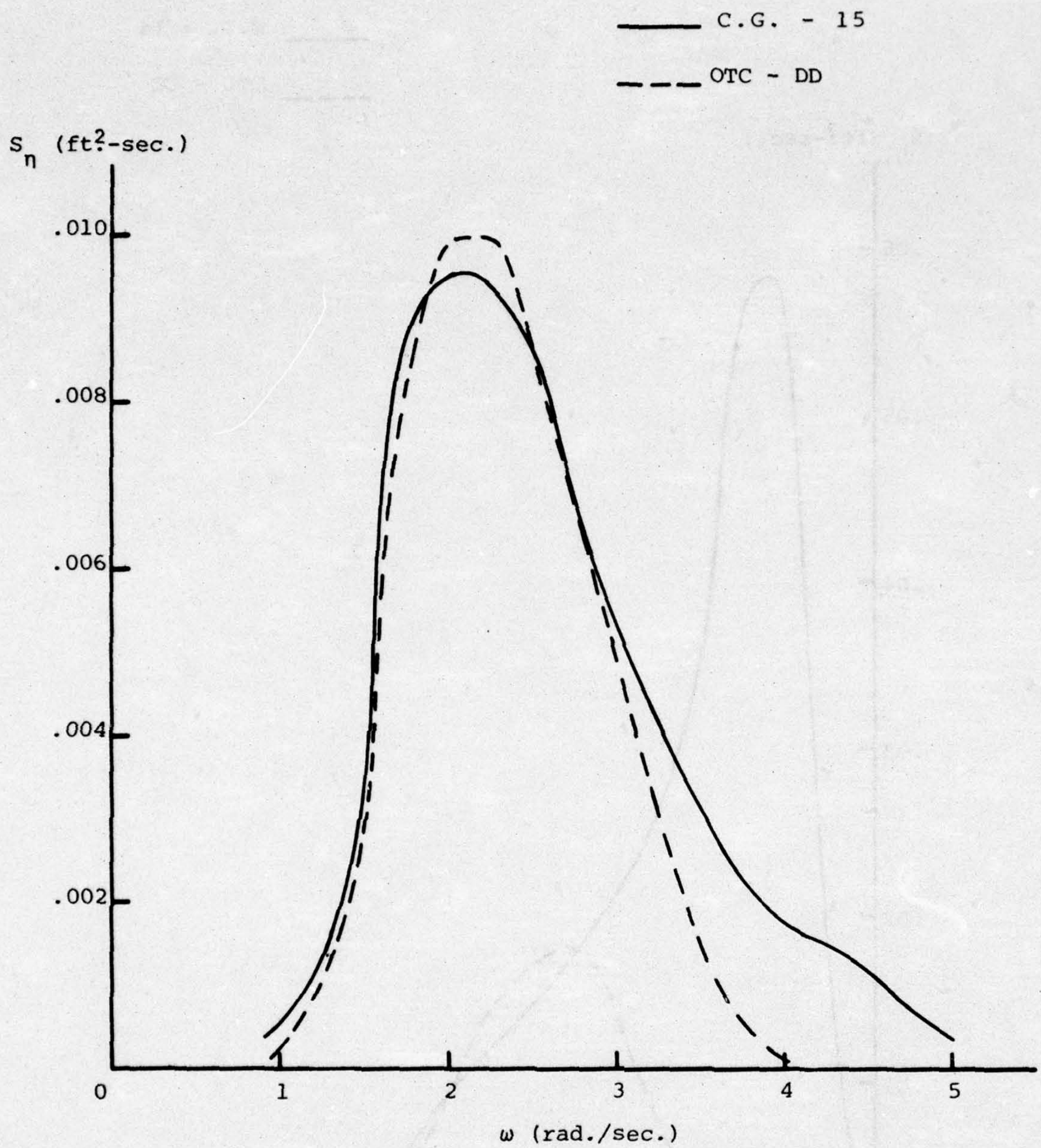

Fig. A.6 Comparison of wave spectra, full scale and model, for Test No. 15

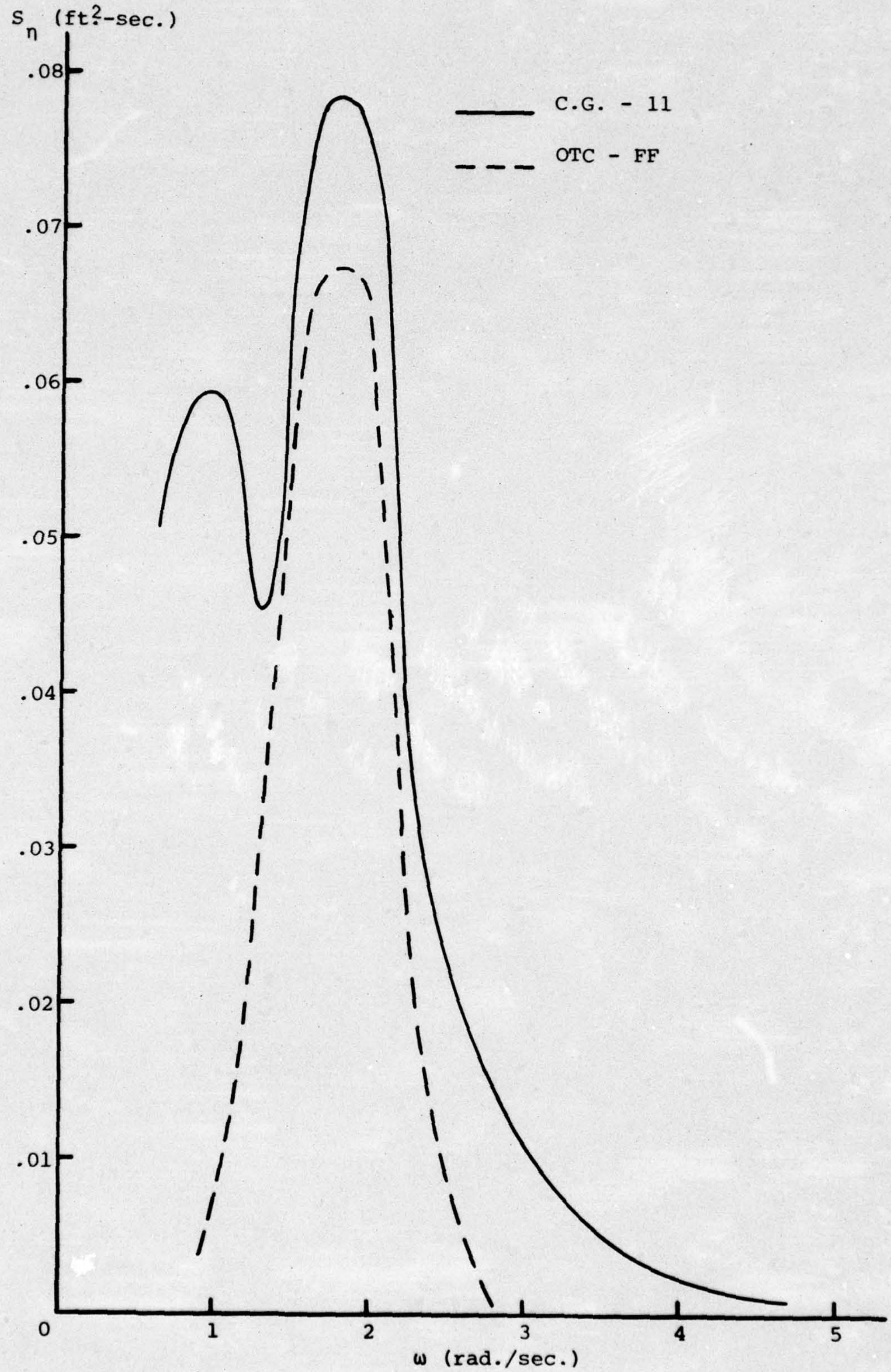

Fig. A.7 Comparison of wave spectra, full scale and model, for Test No. 11

APPENDIX B

COMPARISON OF TRANSIENT DECAY, FULL SCALE AND MODEL

APPENDIX B

		Test No.
1.	Comparison of roll angle transient, full scale and model, jon boat	4
2.	Comparison of roll angle transient, full scale and model, jon boat	1
3.	Comparison of roll angle transient, full scale and model, jon boat	2
4.	Comparison of roll angle transient, full scale and model, jon boat	14
5.	Comparison of roll angle transient, full scale and model, jon boat	15
6.	Comparison of roll angle transient, full scale and model, jon boat	5
7.	Comparison of roll angle transient, full scale and model, jon boat	3 (tank)
8.	Comparison of roll angle transient, full scale and model, jon boat	6
9.	Comparison of roll angle transient, full scale and model, runabout	9
10.	Comparison of pitch angle transient, full scale and model, jon boat	3 (tank)
11.	Comparison of pitch angle transient, full scale and model, jon boat	6
12.	Comparison of pitch angle transient, full scale and model, jon boat	5
13.	Comparison of pitch angle transient, full scale and model, jon boat	4
14.	Comparison of pitch angle transient, full scale and model, jon boat	15
15.	Comparison of pitch angle transient, full scale and model, jon boat	14
16.	Comparison of pitch angle transient, full scale and model, jon boat	2
17.	Comparison of pitch angle transient, full scale and model, jon boat	1
18.	Comparison of pitch angle transient, full scale and model, runabout	9

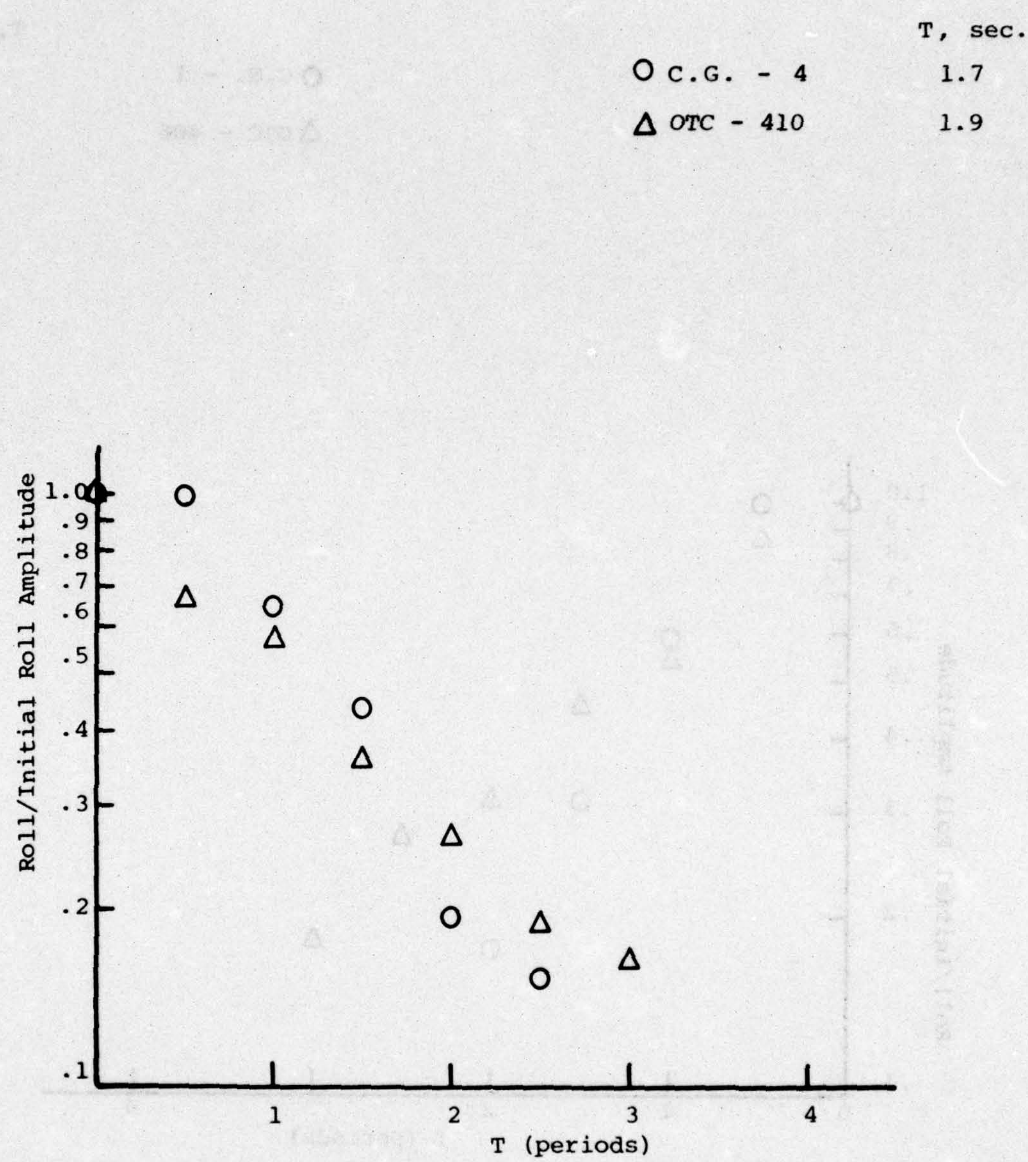

Fig. B.1 Comparison of roll angle transient, full scale and model, jon boat, Test No. 4

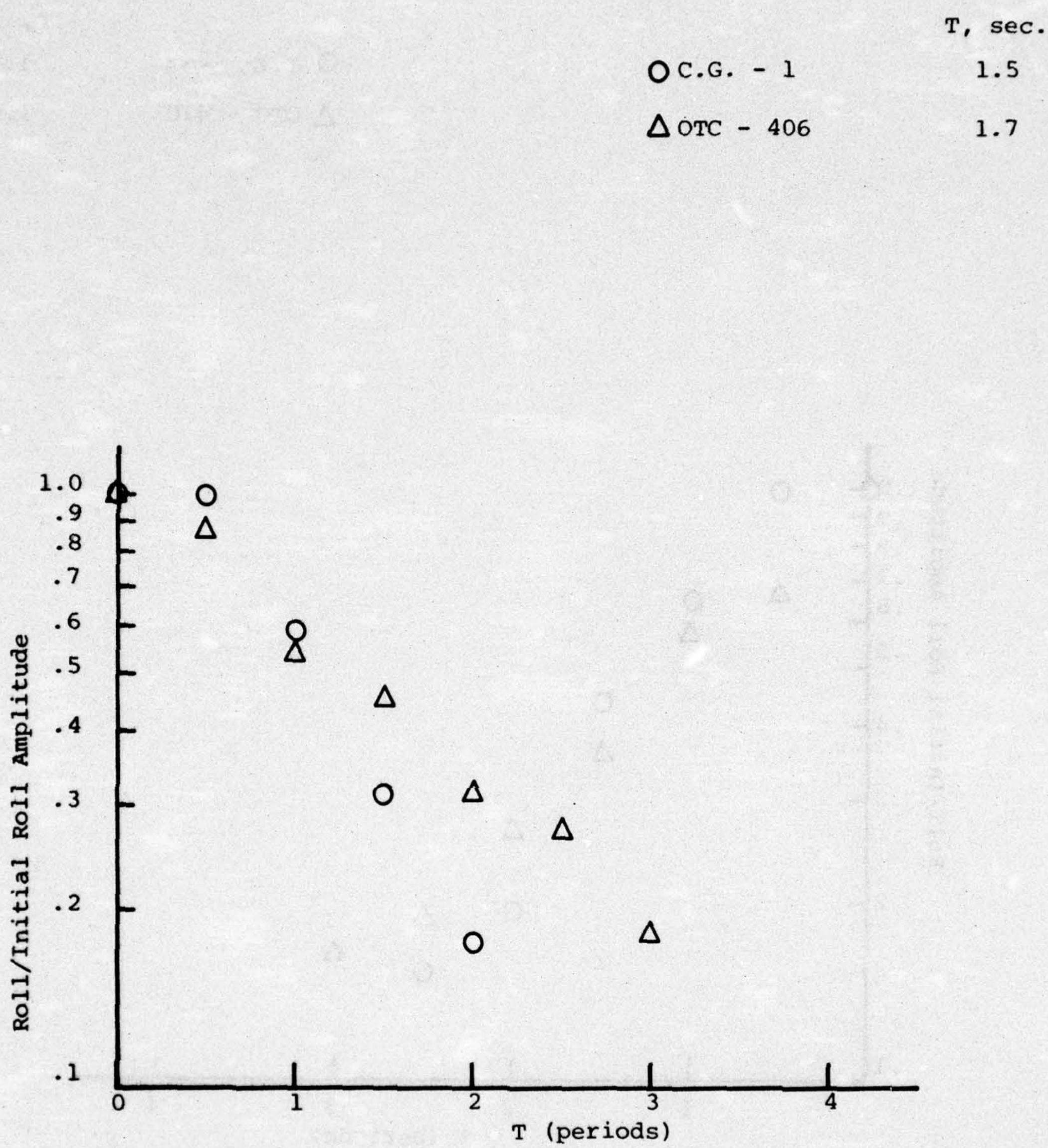

Fig. B.2 Comparison of roll angle transient, full scale and model, jon boat, Test No. 1

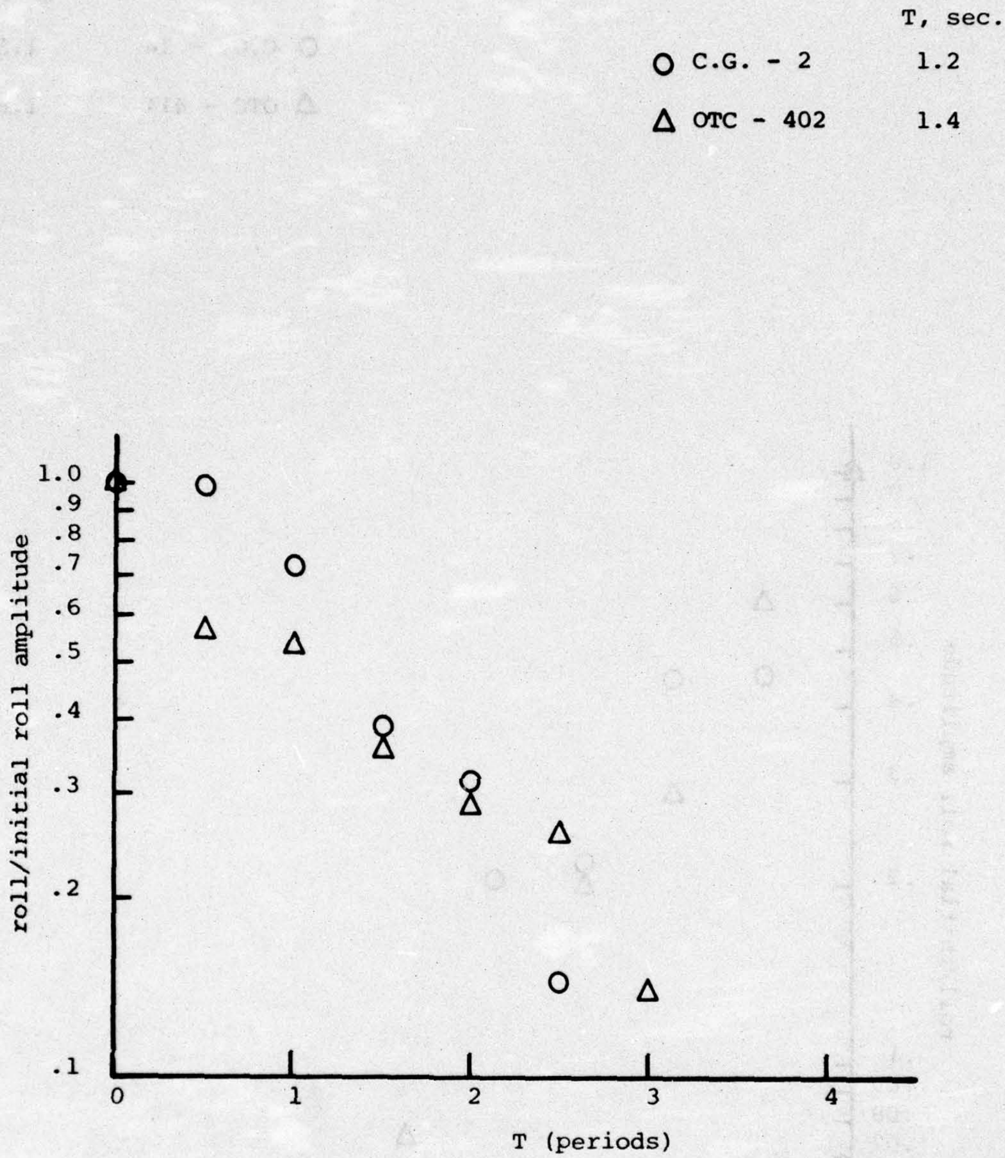

Fig. B.3 Comparison of roll angle transient, full scale and model, jon boat, Test No. 2

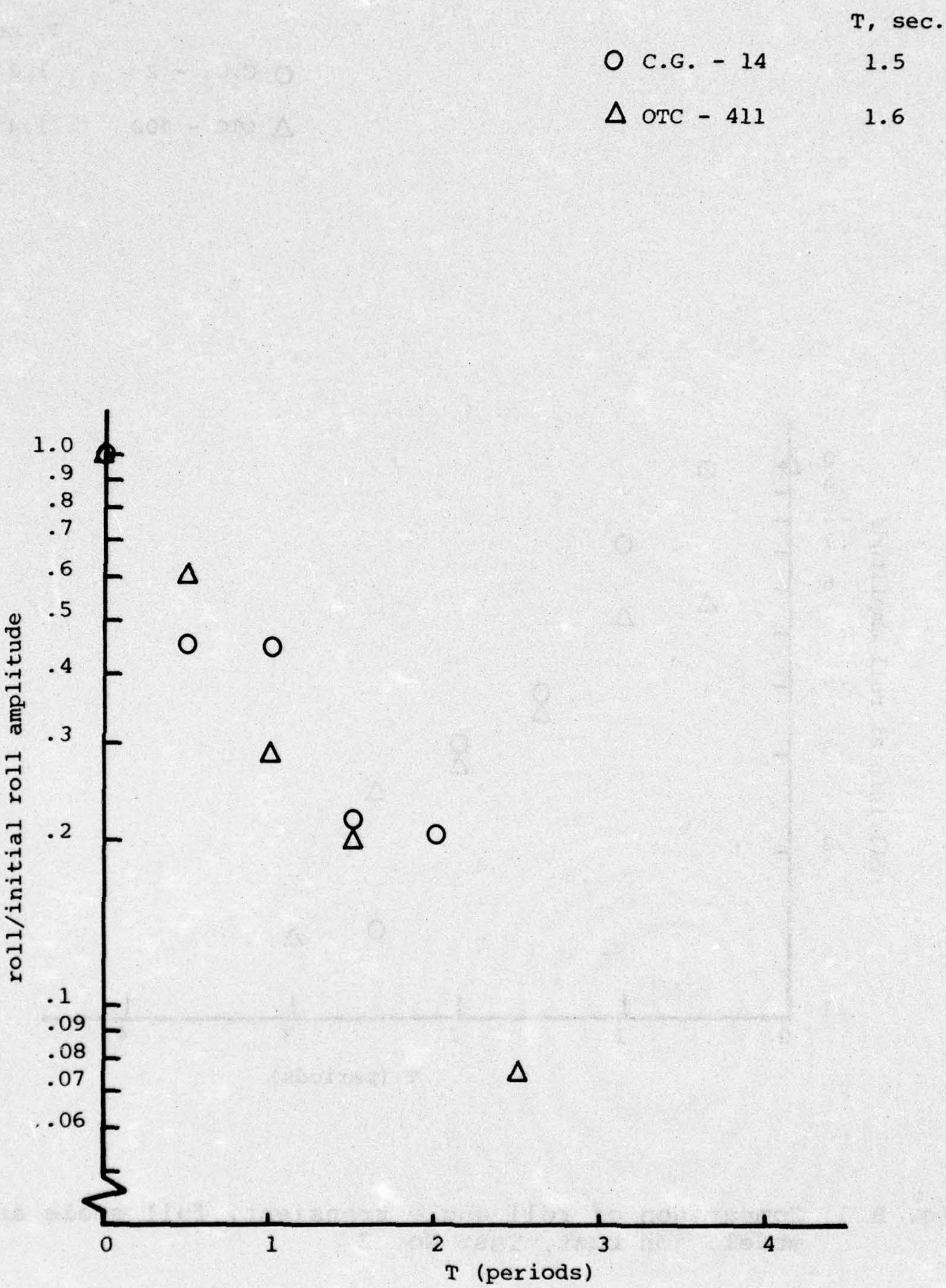

Fig. B.4 Comparison of roll angle transient, full scale and model, jon boat, Test No. 14

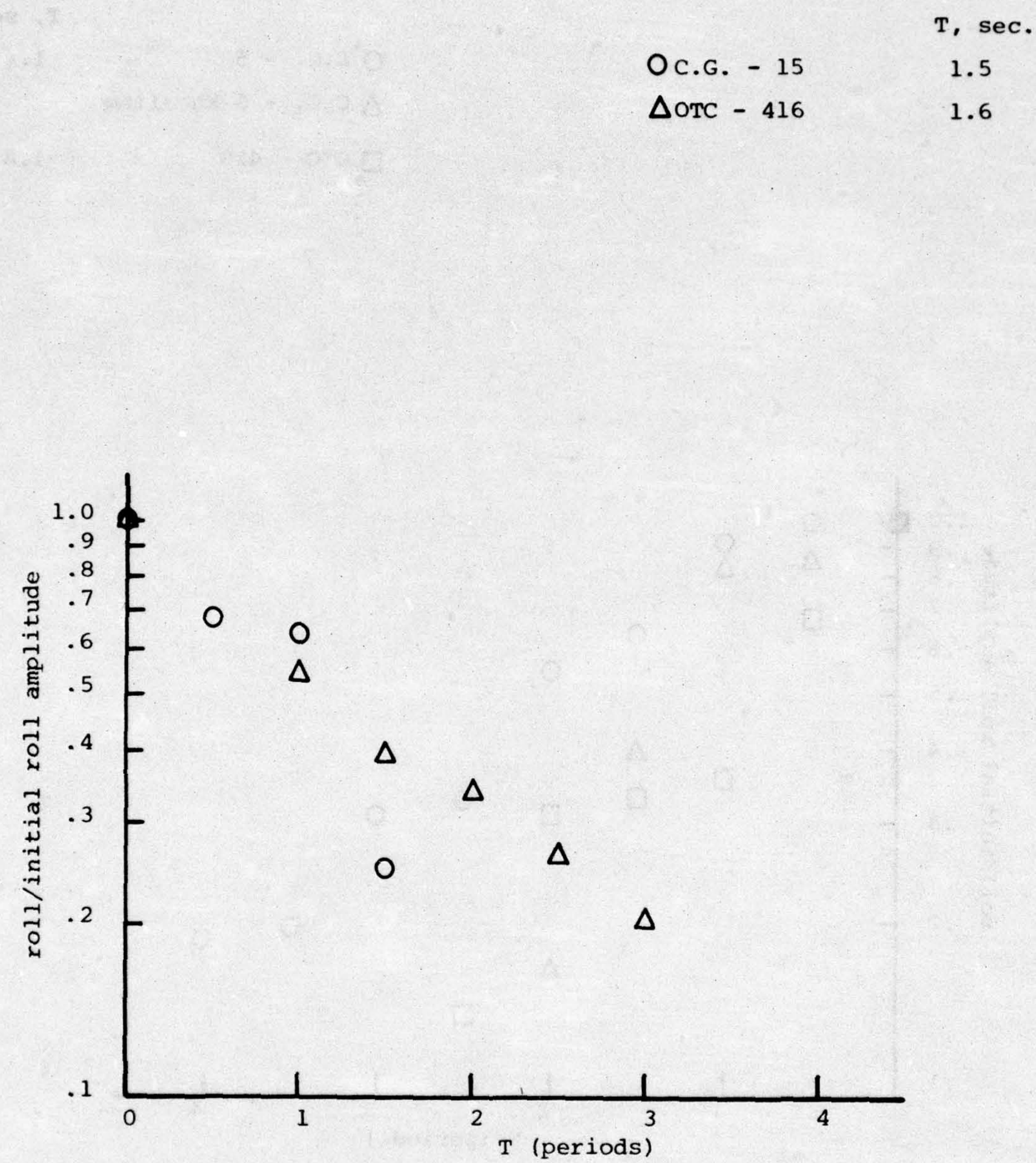

Fig. B.5 Comparison of roll angle transient, full scale and model, jon boat, Test No. 15

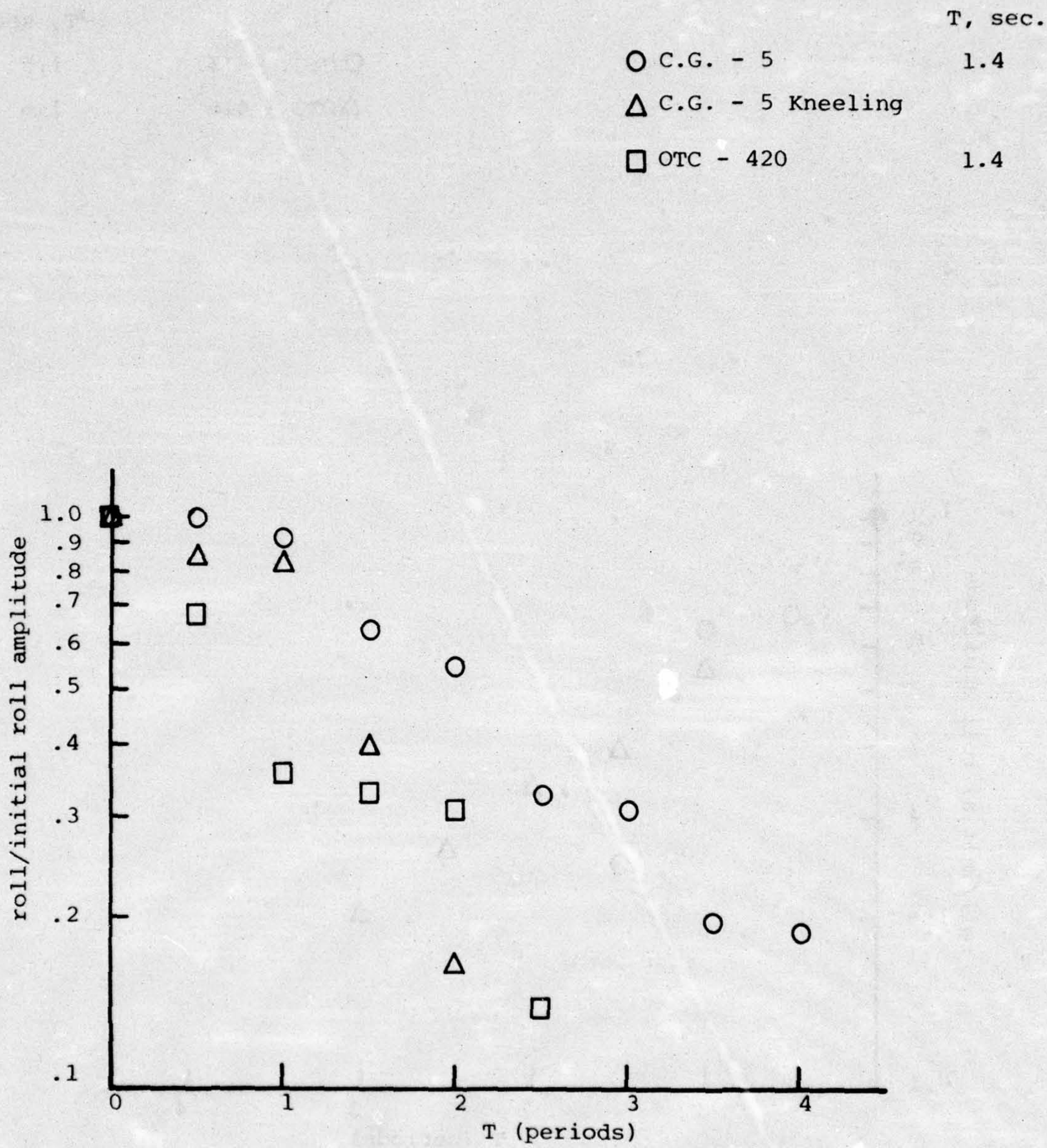

Fig. B.6 Comparison of roll angle transient, full scale and model, jon boat, Test No. 5

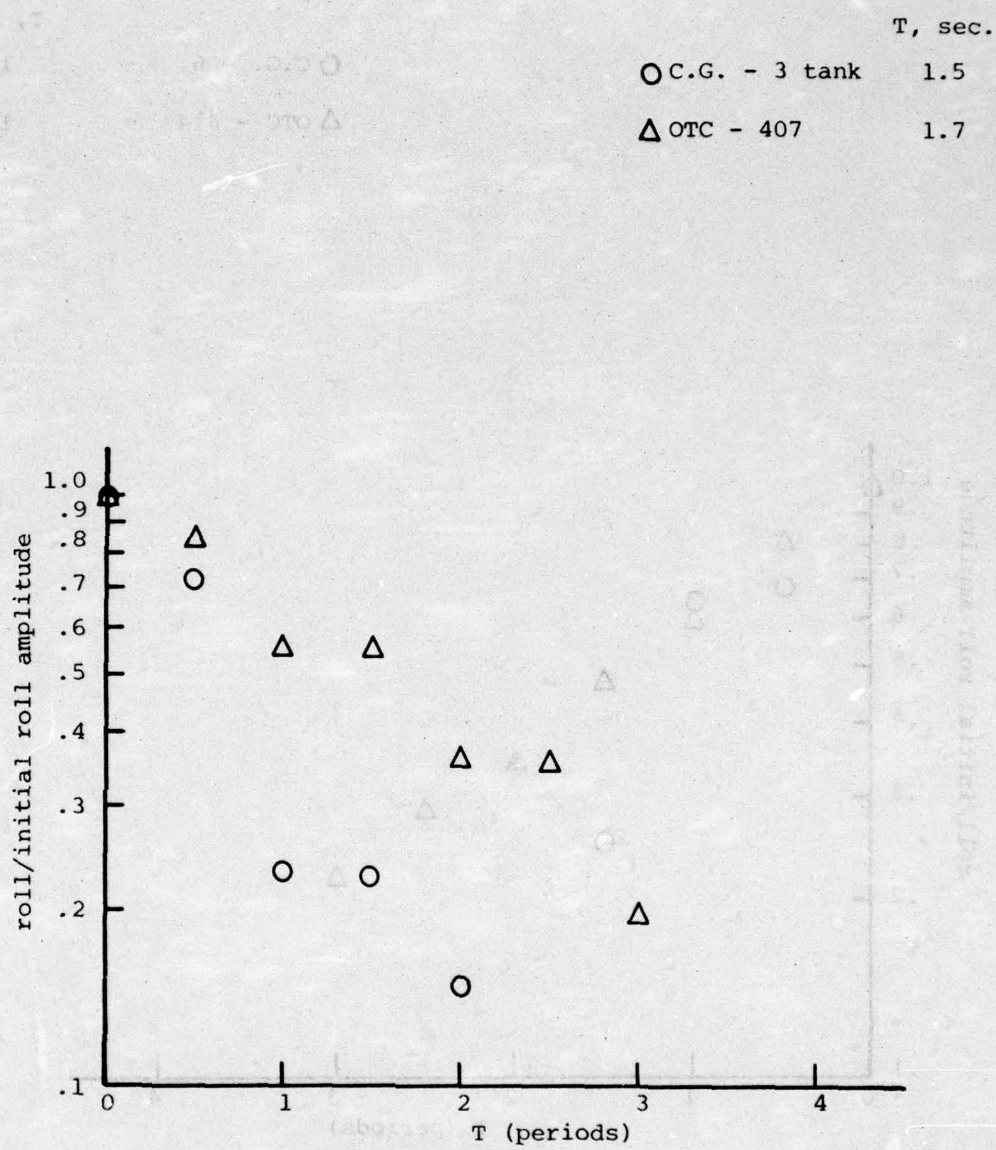

Fig. B.7 Comparison of roll angle transient, full scale and model, jon boat, Test No. 3 (tank)

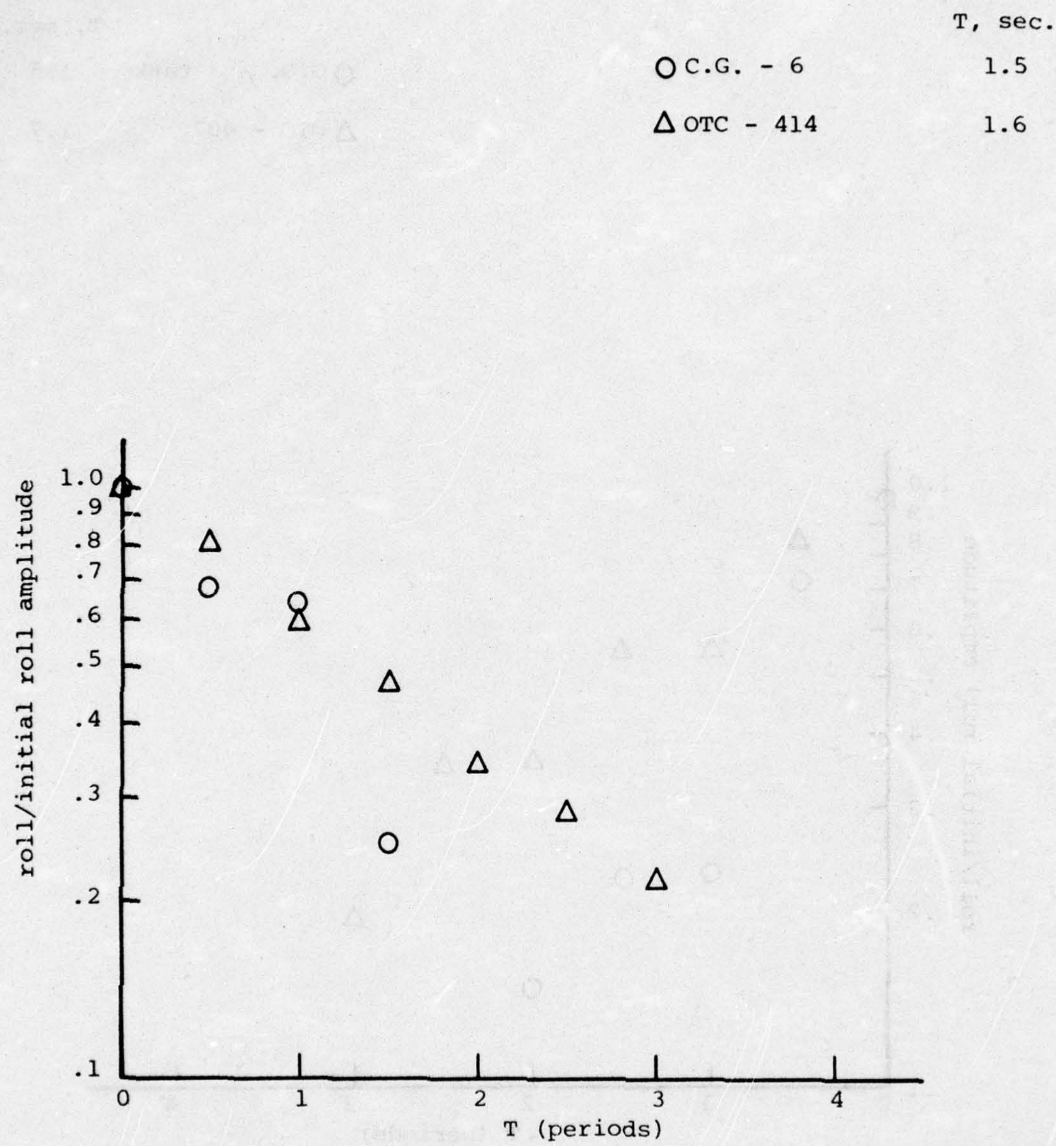

Fig. B.8 Comparison of roll angle transient, full scale and model, jon boat, Test No. 6

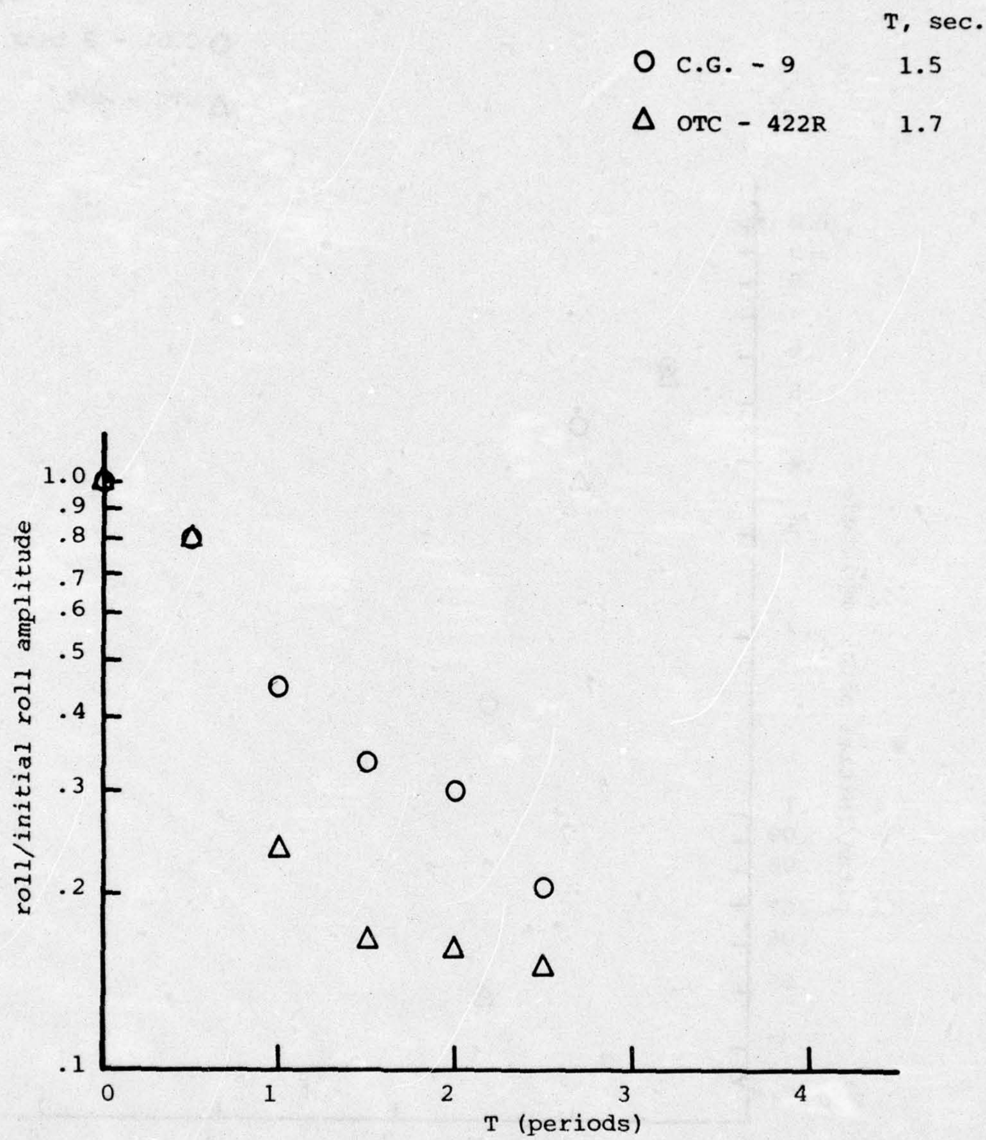

Fig. B.9 Comparison of roll angle transient, full scale and model, runabout, Test No. 9

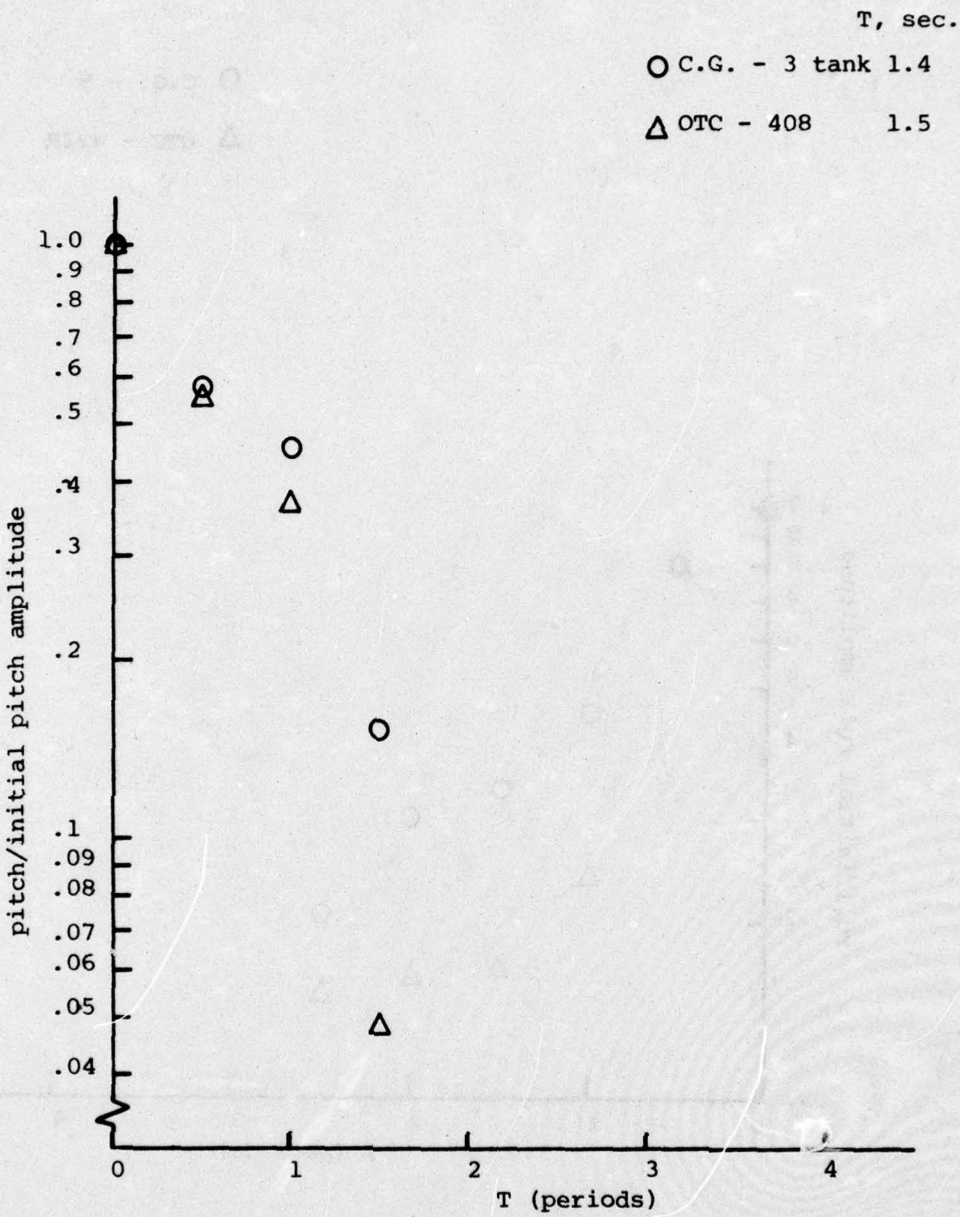

Fig. B.10 Comparison of pitch angle transient, full scale and model, jon boat, Test No. 3 (tank)

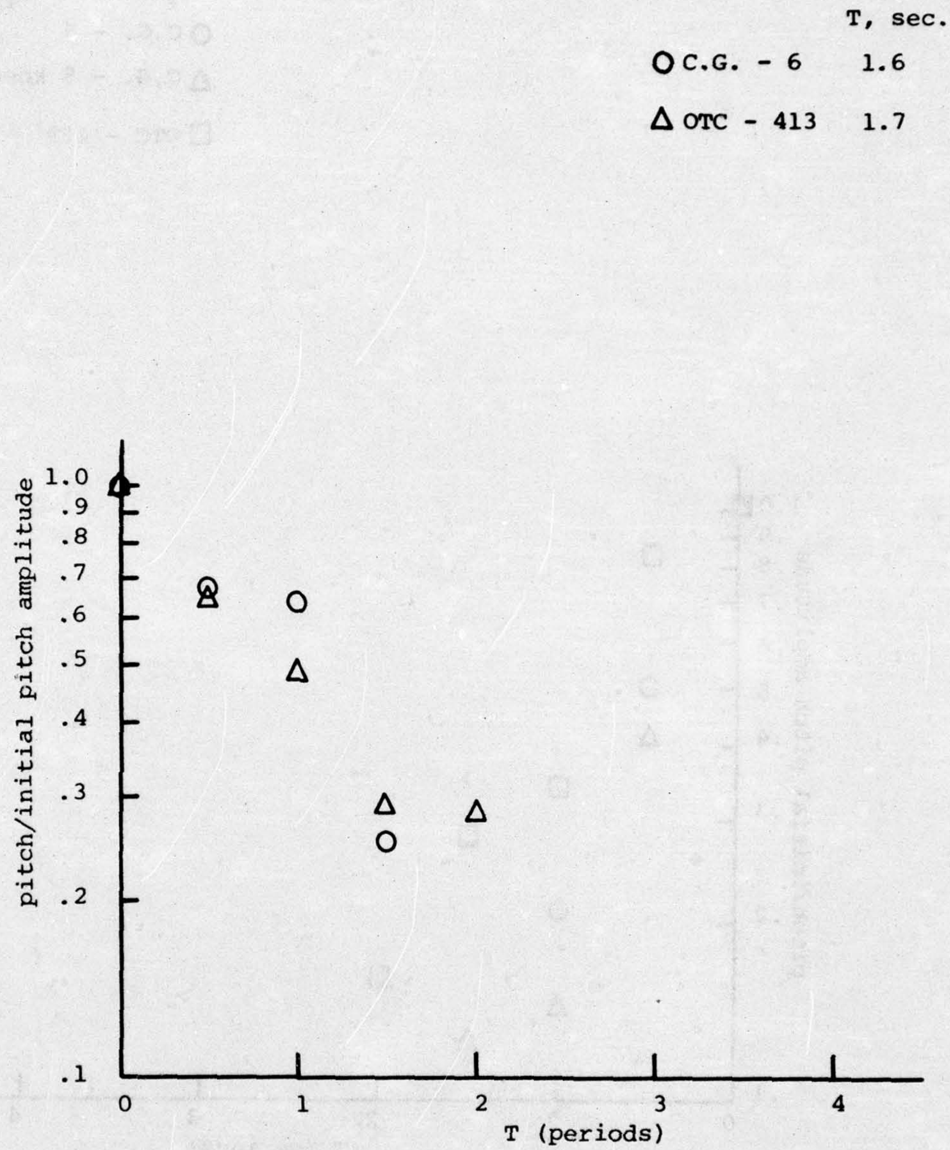

Fig. B.11 Comparison of pitch angle transient, full scale and model, jon boat, Test No. 6

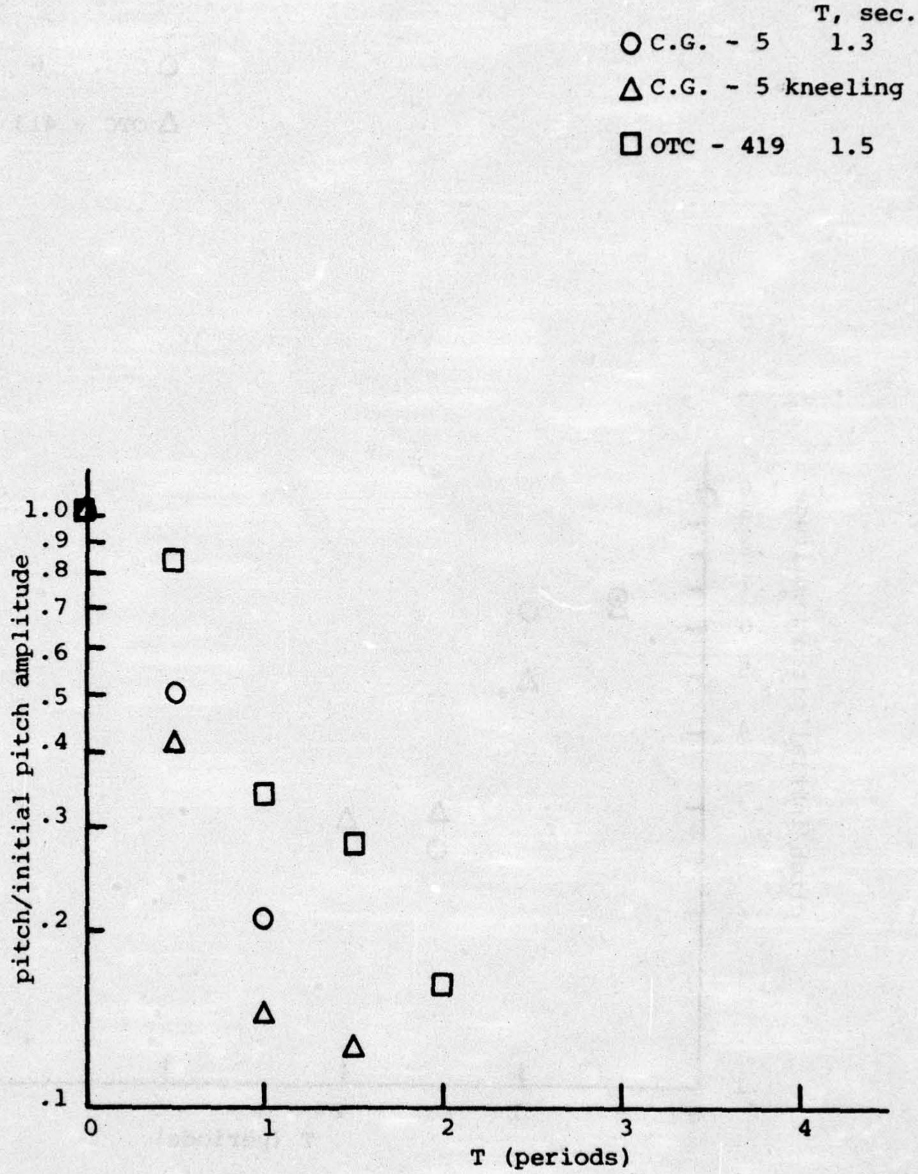

Fig. B.12 Comparison of pitch angle transient, full scale and model, jon boat, Test No. 5

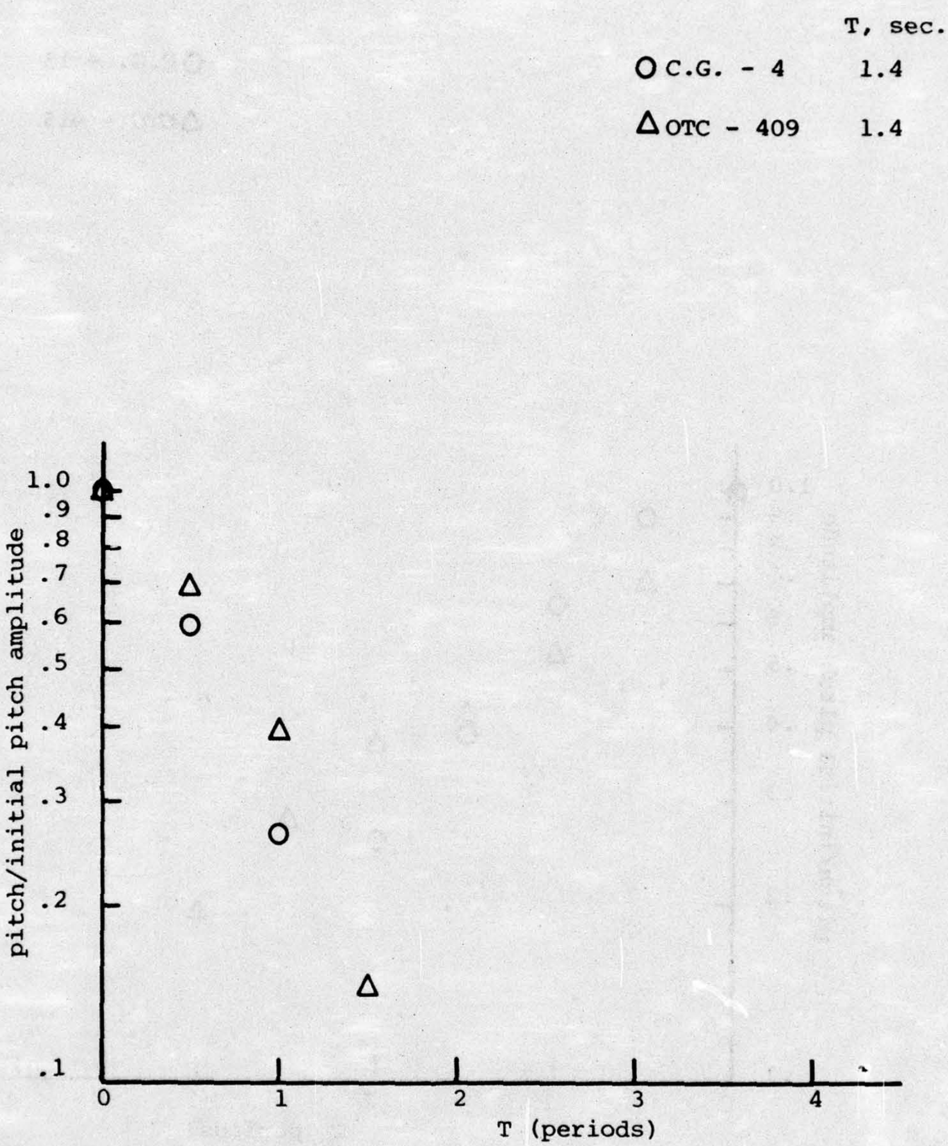

Fig. B.13 Comparison of pitch angle transient, full scale and model, jon boat, Test No. 4

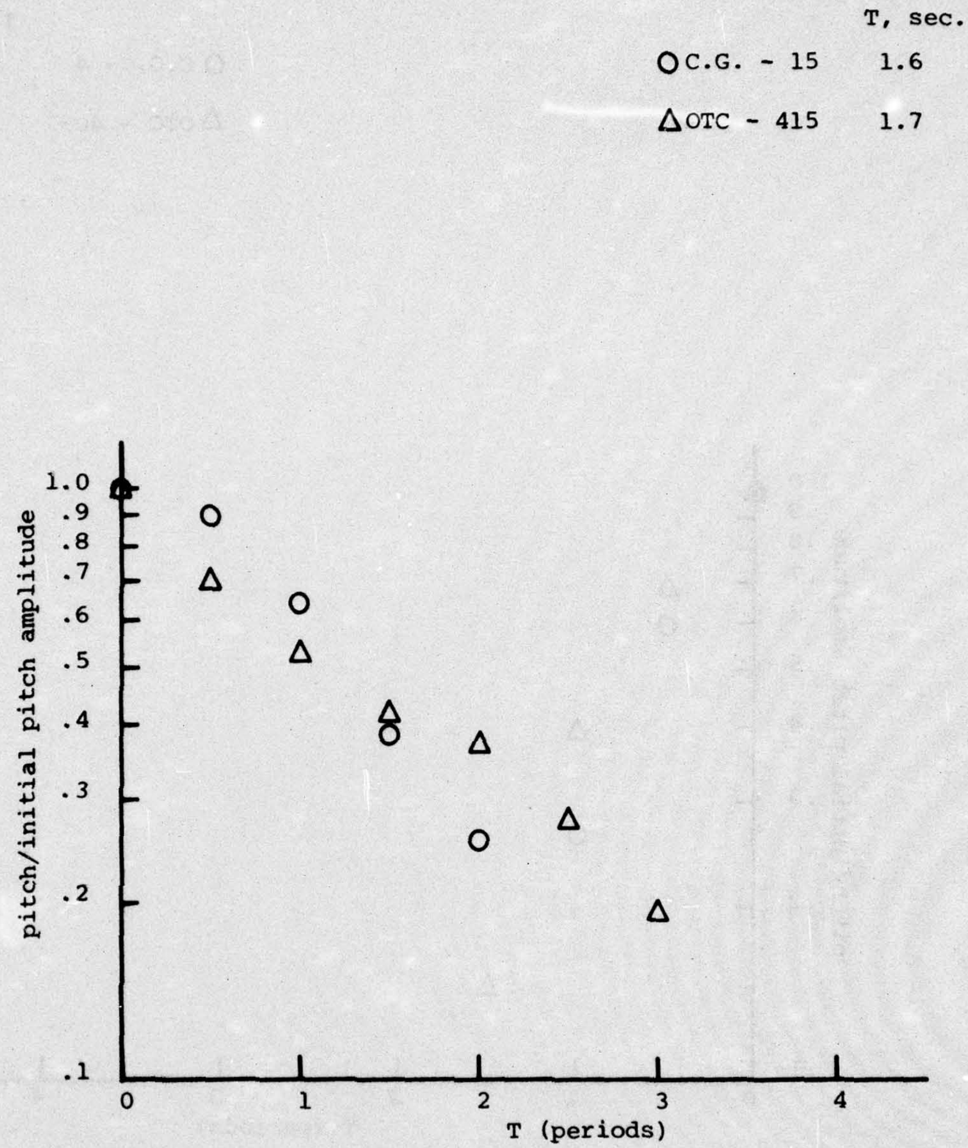

Fig. B.14 Comparison of pitch angle transient, full scale and model, jon boat, Test No. 15

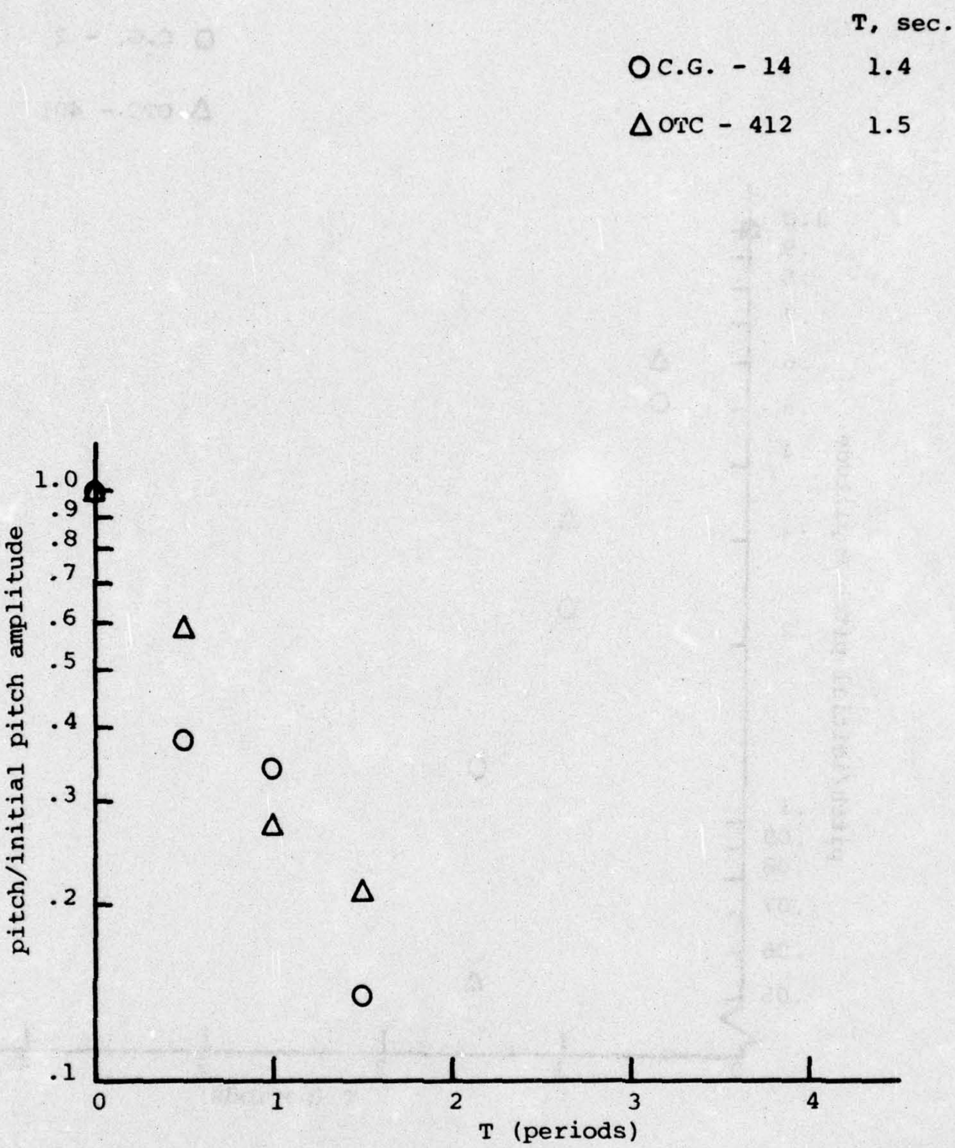

Fig. B.15 Comparison of pitch angle transient, full scale and model, jon boat, Test No. 14

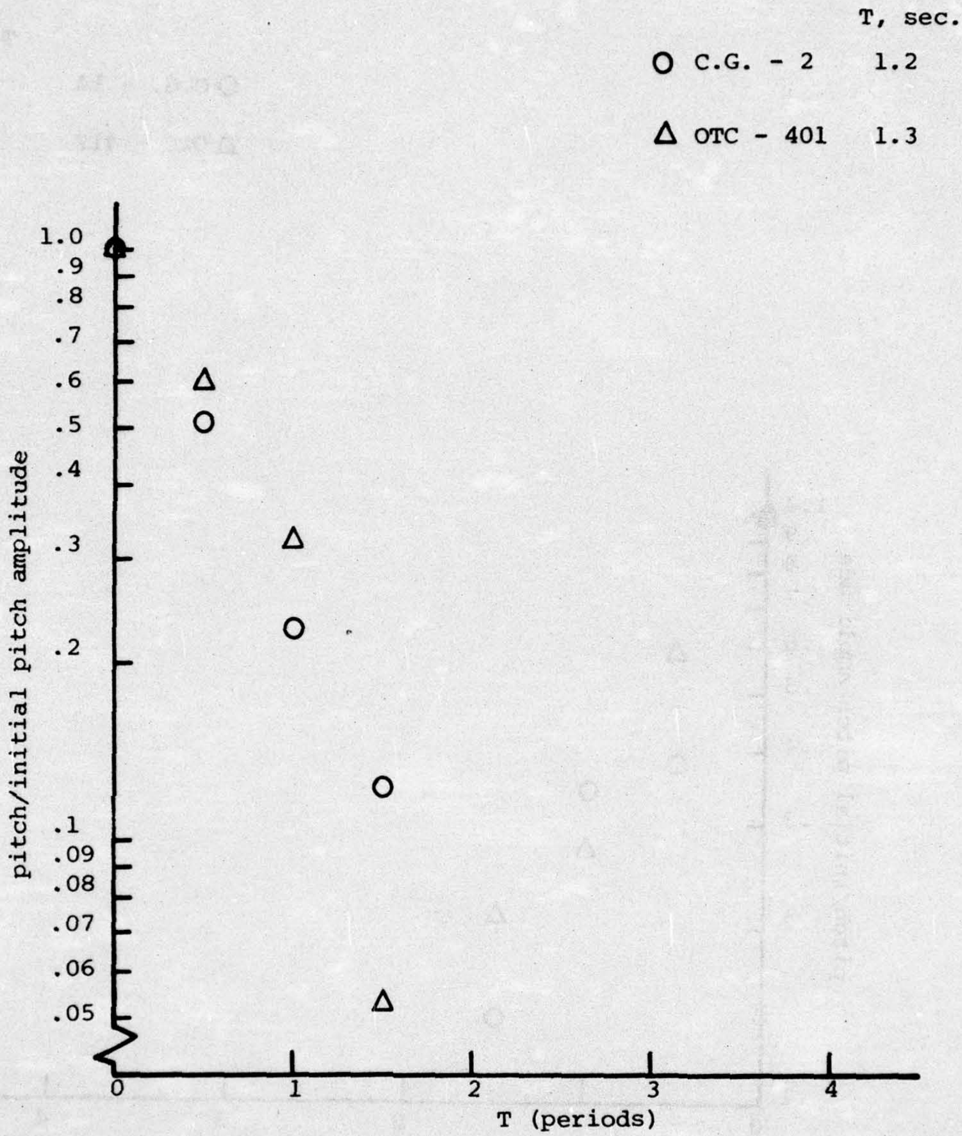

Fig. B.16 Comparison of pitch angle transient, full scale and model, jon boat, Test No. 2

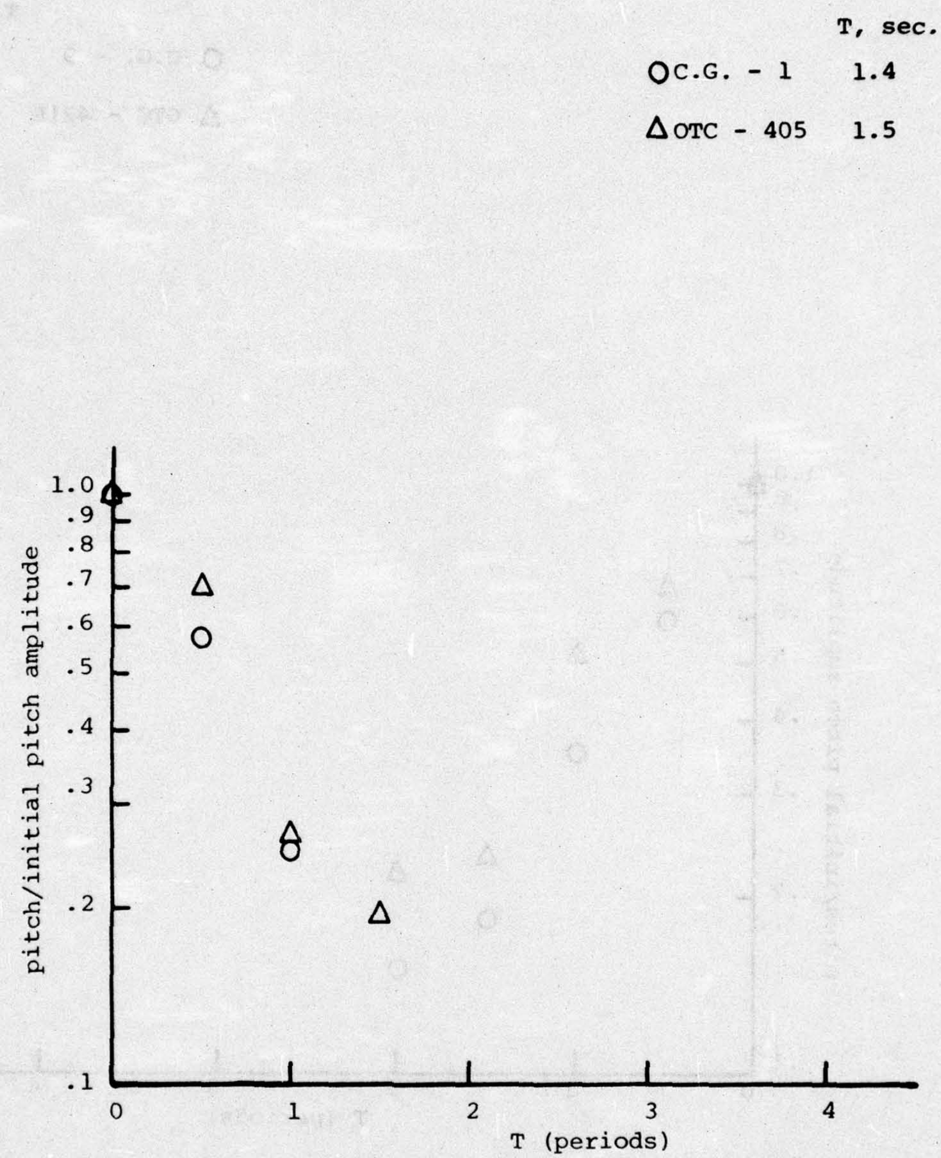

Fig. B.17 Comparison of pitch angle transient, full scale and model, jon boat, Test No. 1

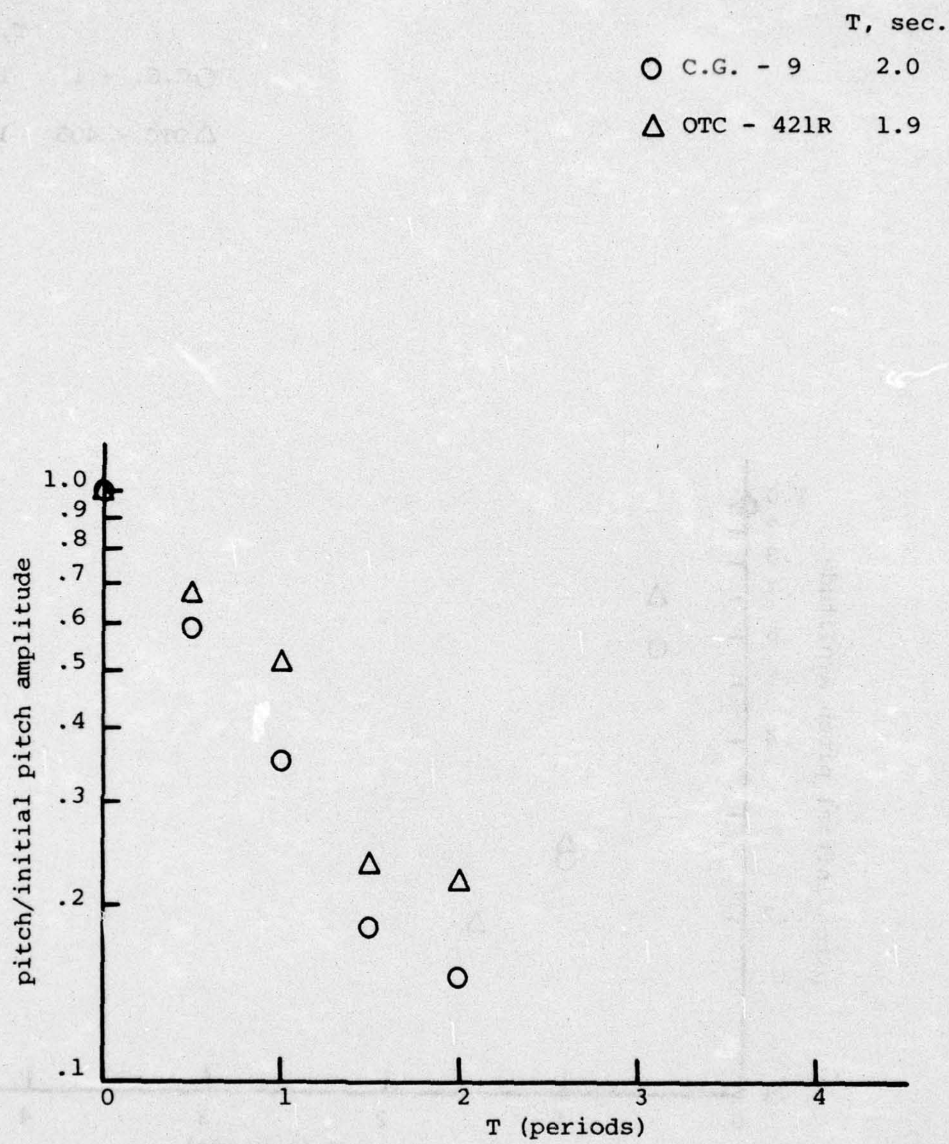

Fig. B.18 Comparison of pitch angle transient, full scale and model, runabout, Test No. 9

APPENDIX C

COMPARISON OF RESPONSE AMPLITUDE OPERATORS, MODEL TESTS IN REGULAR WAVES AND RANDOM WAVES

APPENDIX C

1. Comparison of roll RAO for jon boat, beam seas, for regular waves and random waves
2. Comparison of sway RAO for jon boat, beam seas, for regular waves and random waves
3. Comparison of heave RAO for jon boat, beam seas, for regular waves and random waves
4. Comparison of gunwale freeboard RAO for jon boat, beam seas, for regular waves and random waves
5. Comparison of pitch RAO for jon boat, head seas, for regular waves and random waves
6. Comparison of heave RAO for jon boat, head seas, for regular waves and random waves
7. Comparison of freeboard RAO for jon boat, head seas, for regular waves and random waves
8. Comparison of heave RAO for runabout, head seas, for regular waves and random waves
9. Comparison of pitch RAO for runabout, head seas, for regular waves and random waves
10. Comparison of freeboard RAO for runabout, head seas, for regular waves and random waves
11. Comparison of heave RAO for runabout, beam seas, for regular waves and random waves
12. Comparison of roll RAO for runabout, beam seas, for regular waves and random waves
13. Comparison of sway RAO for runabout, beam seas, for regular waves and random waves
14. Comparison of gunwale freeboard RAO for runabout, beam seas, for regular waves and random waves

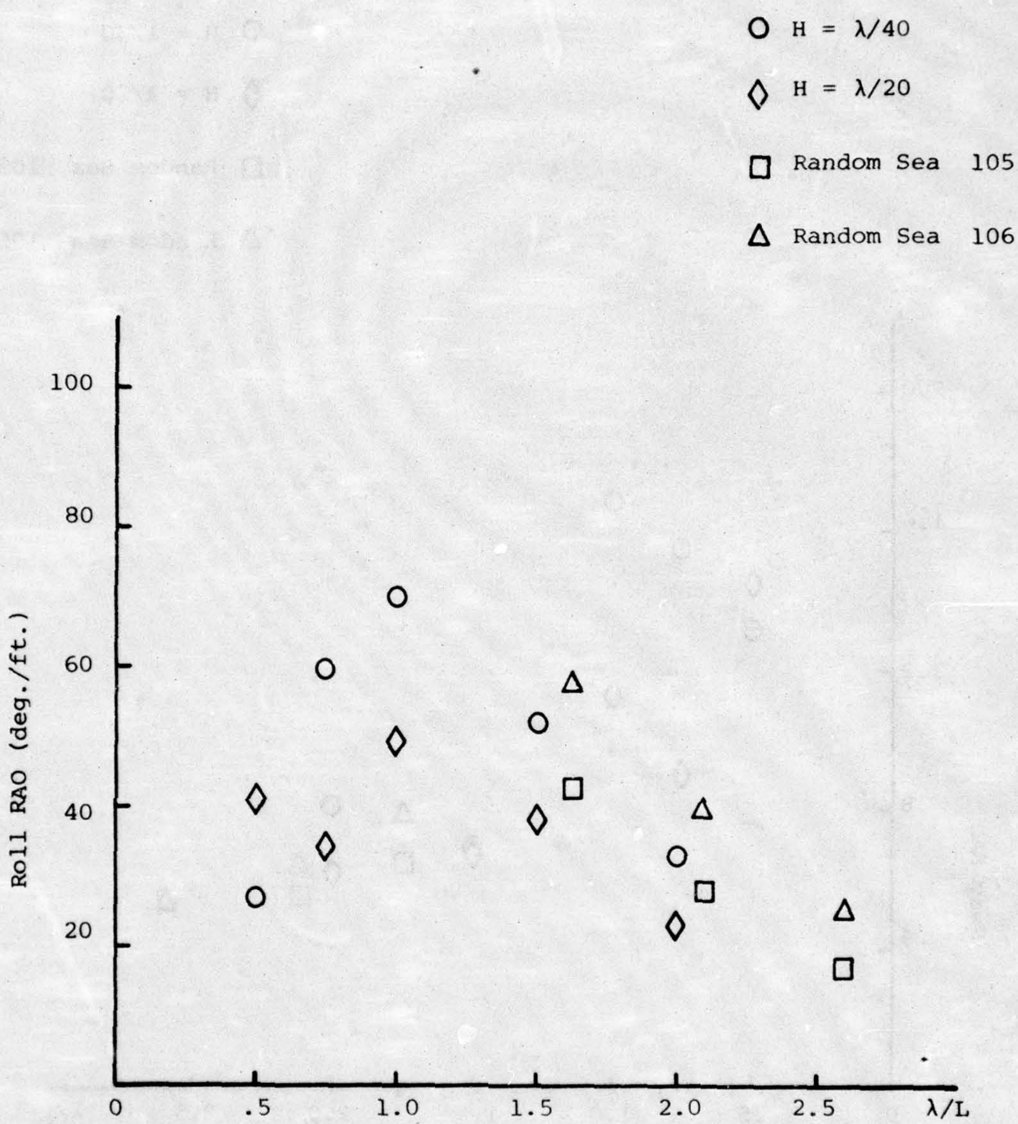

Fig. C.1 Comparison of roll RAO for jon boat, beam seas, for regular waves and random waves

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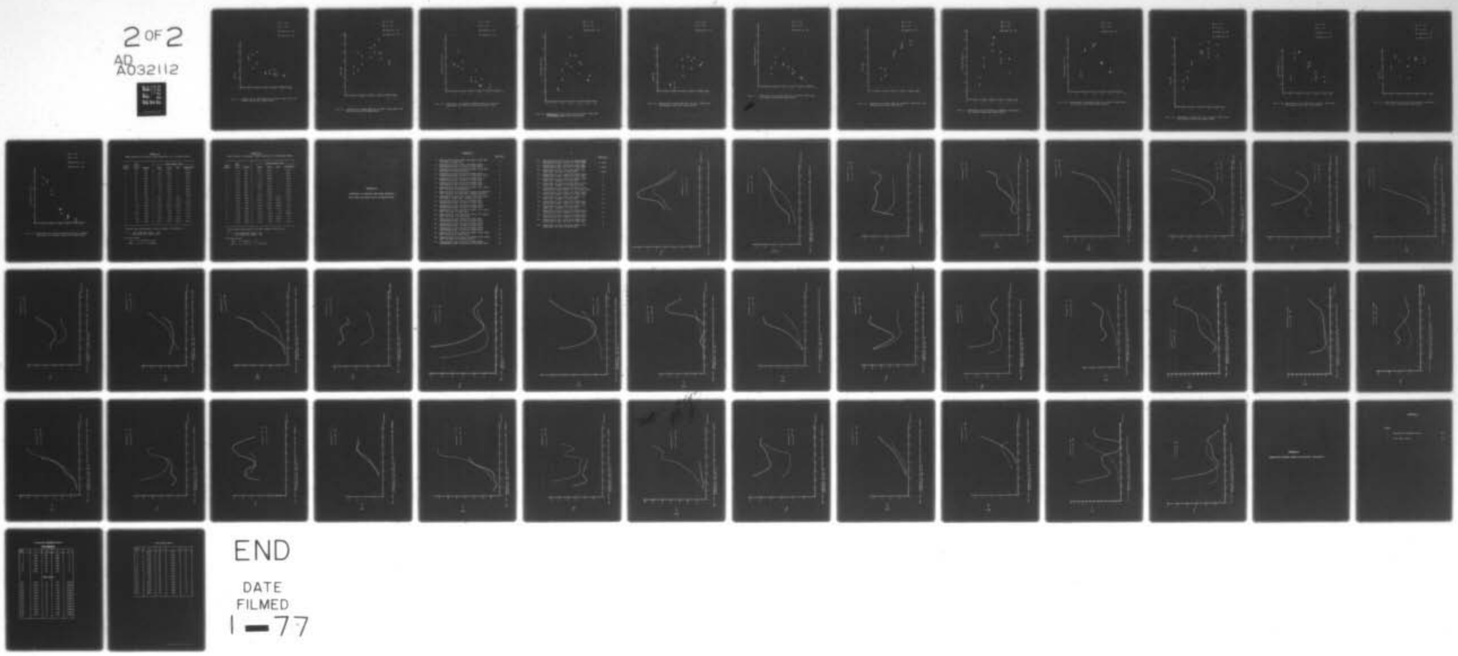

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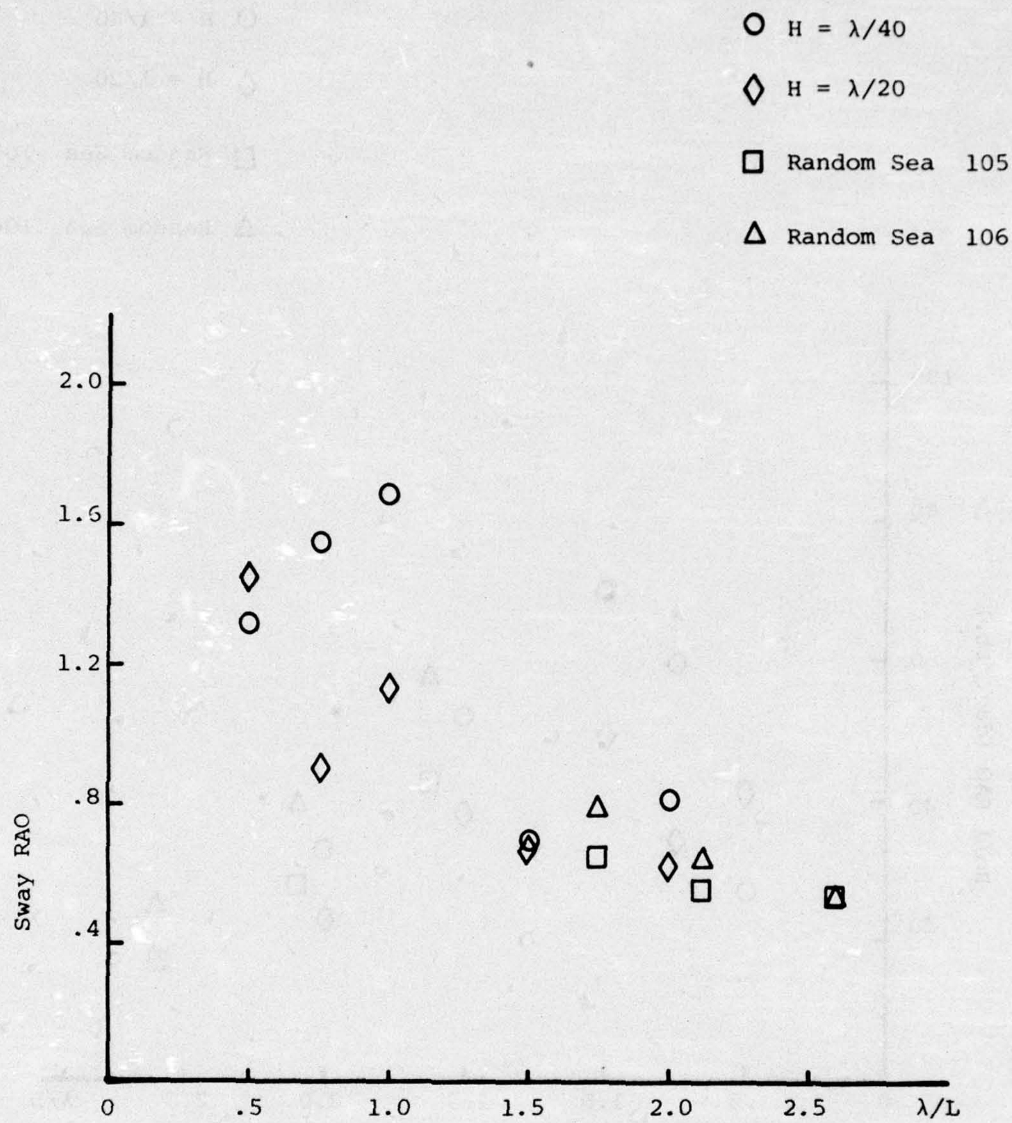

Fig. C.2 Comparison of sway RAO for jon boat, beam seas, for regular waves and random waves

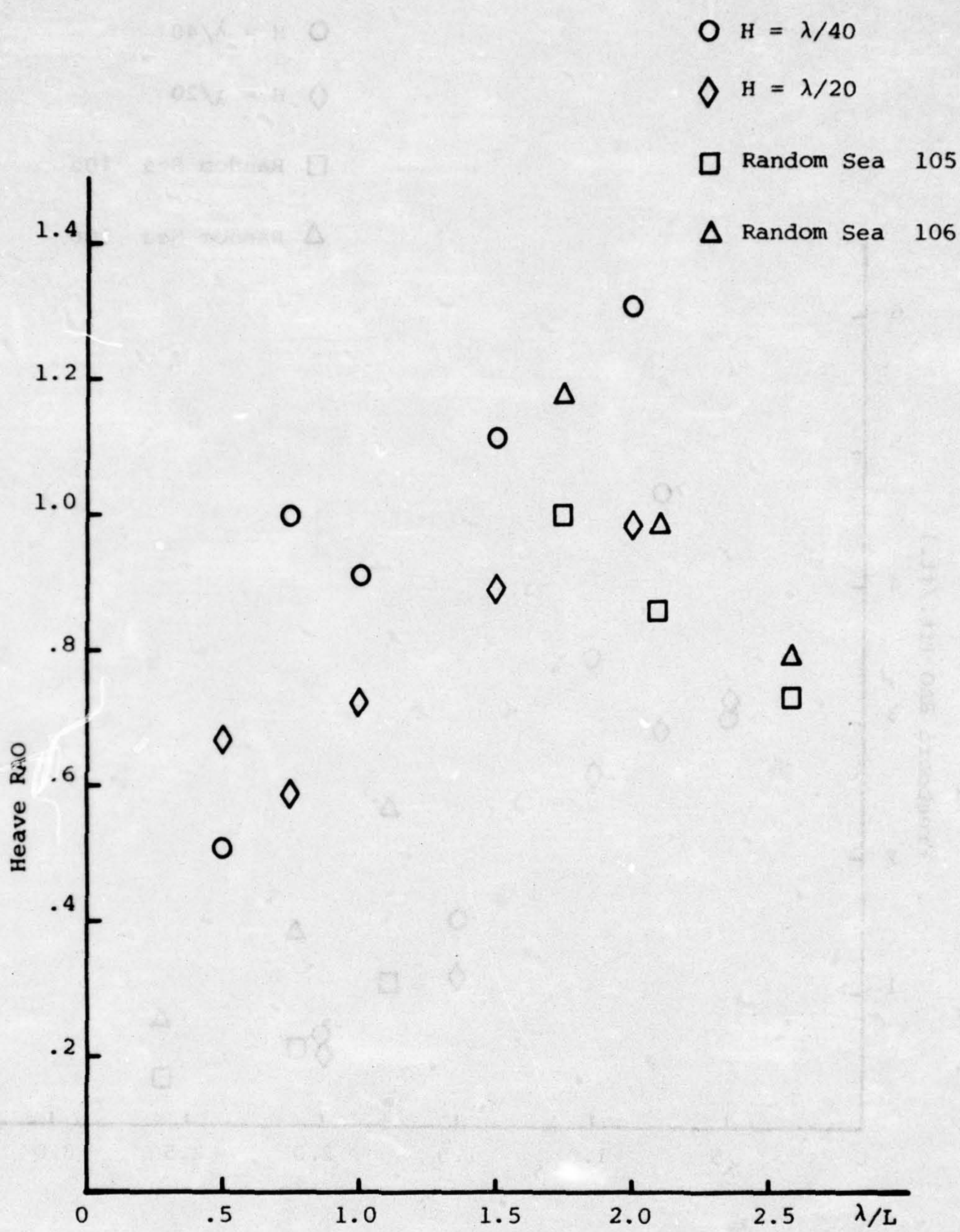

Fig. C.3 Comparison of heave RAO for jon boat, beam seas, for regular waves and random waves

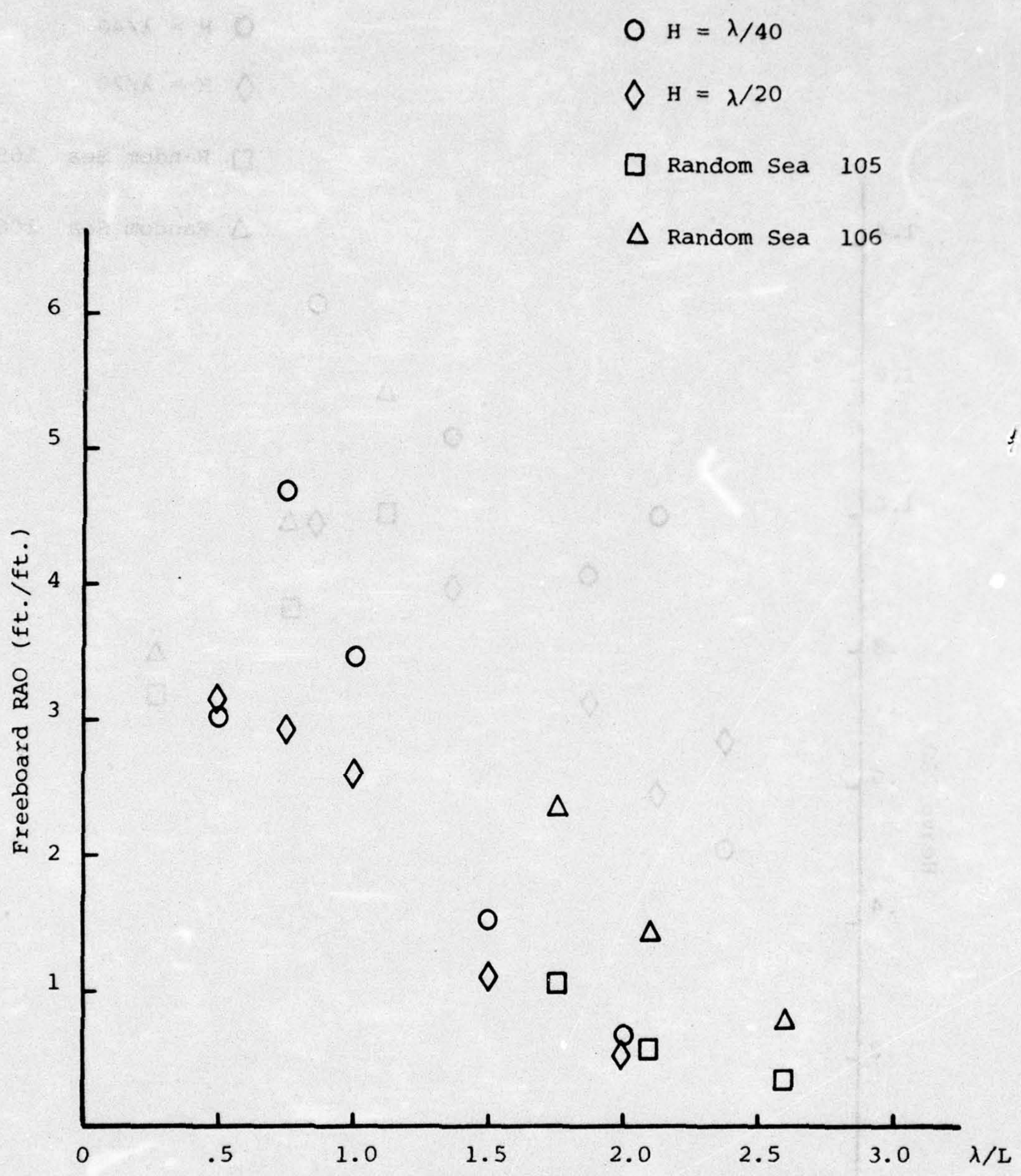

Fig. C.4 Comparison of gunwale freeboard RAO for jon boat, beam seas, for regular waves and random waves

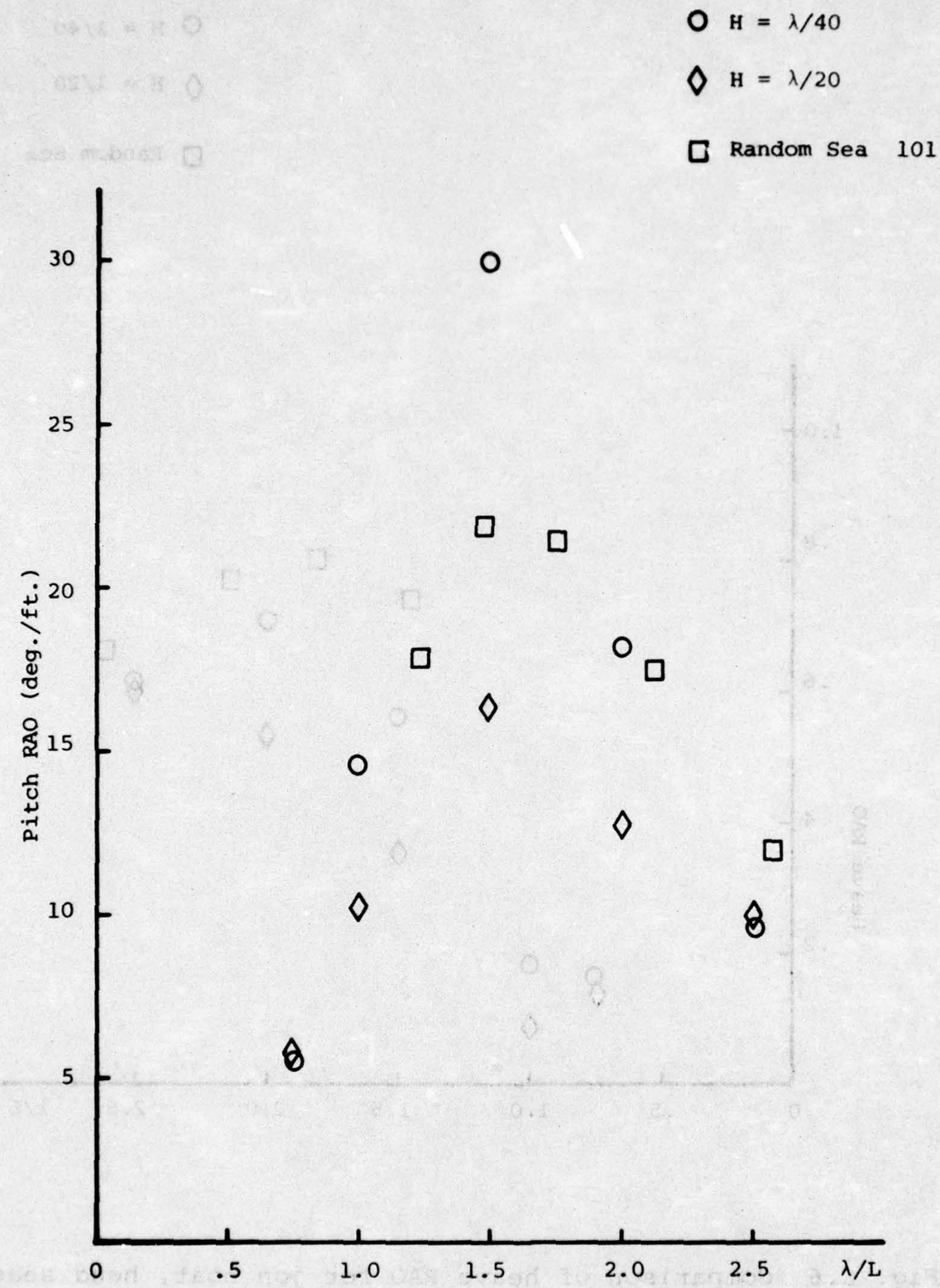

Fig. C.5 **Comparison** of pitch RAO for jon boat, head seas, **for regular** waves and random waves

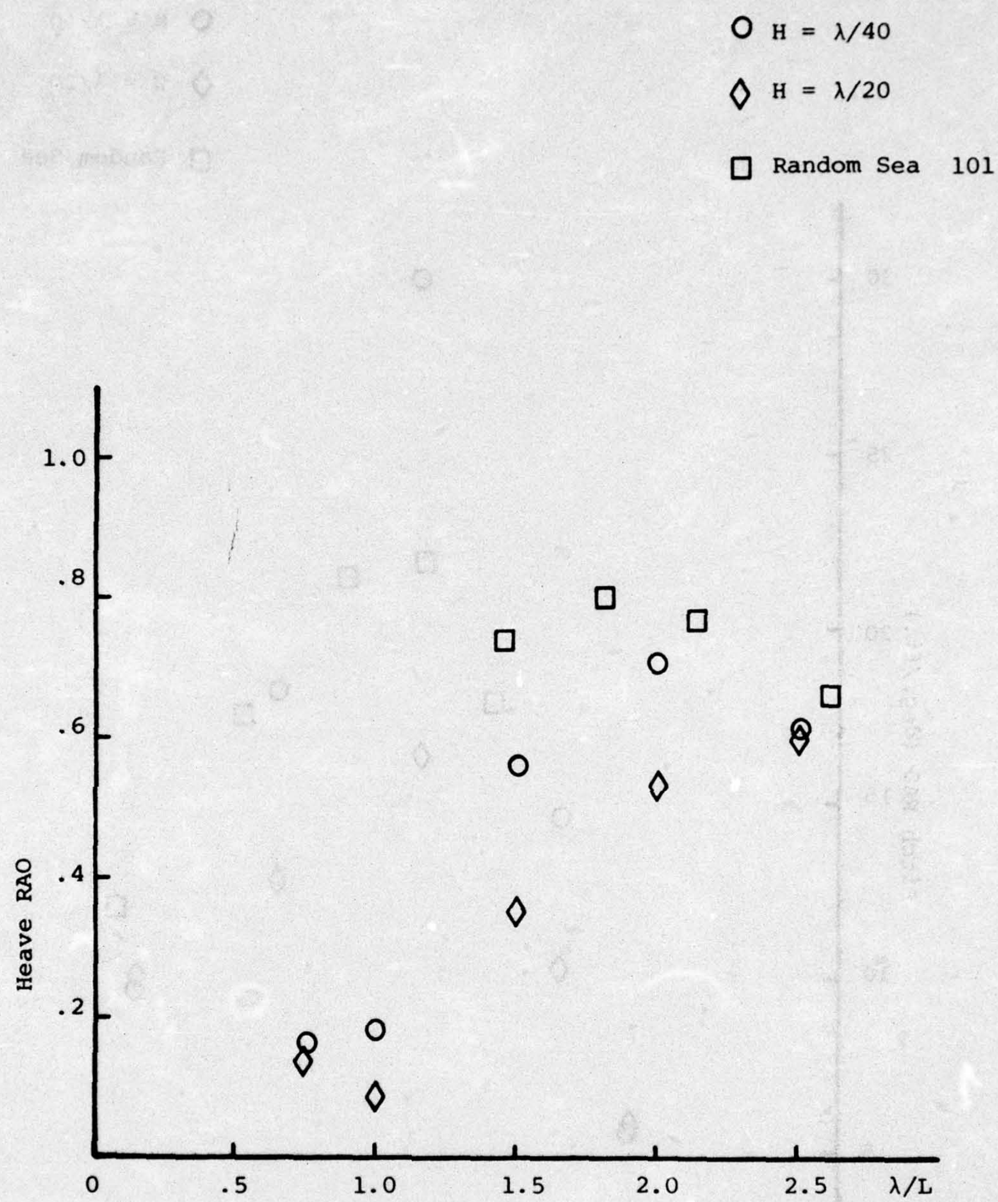

Fig. C.6 Comparison of heave RAO for jon boat, head seas, for regular waves and random waves

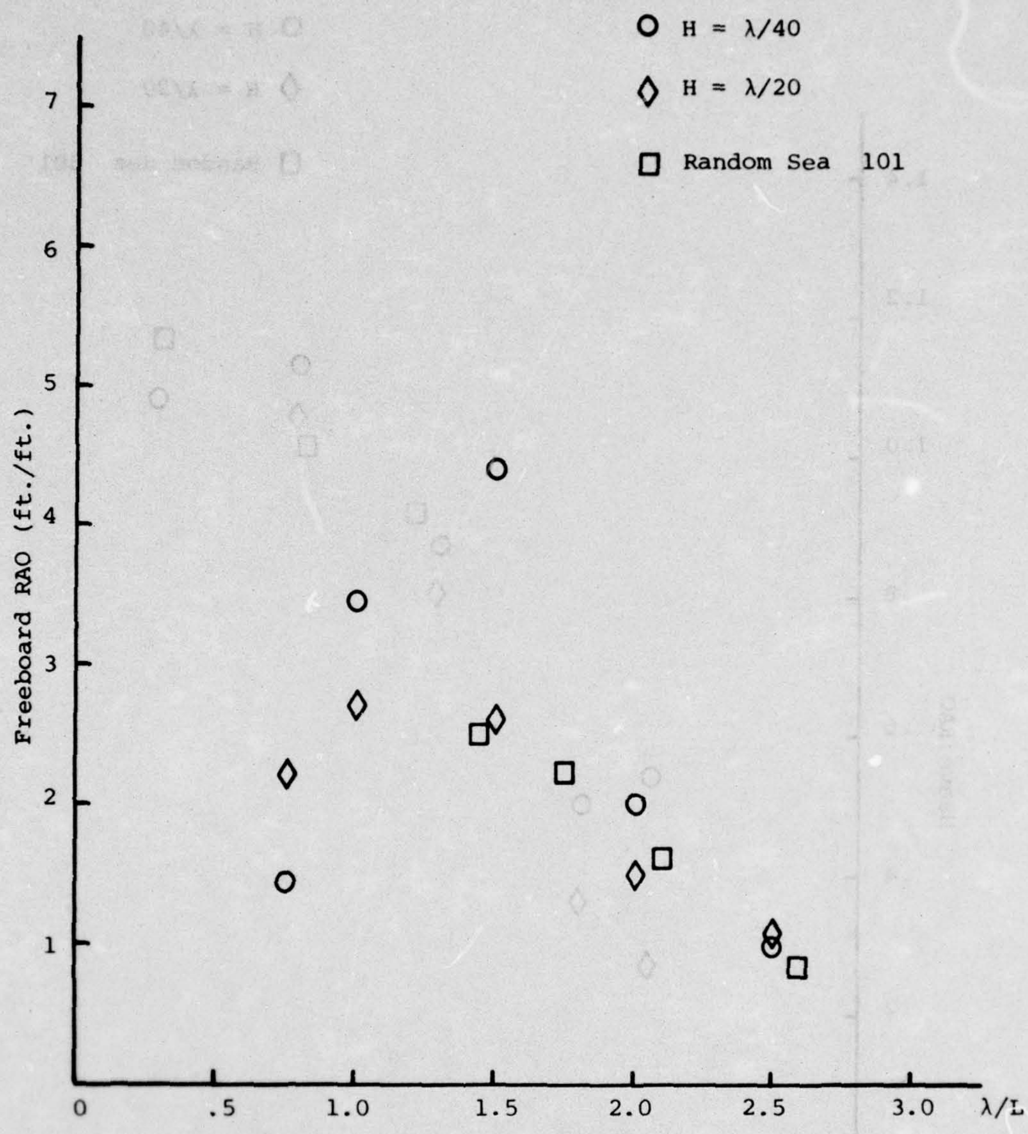

Fig. C.7 Comparison of freeboard RAO for jon boat, head seas, for regular waves and random waves

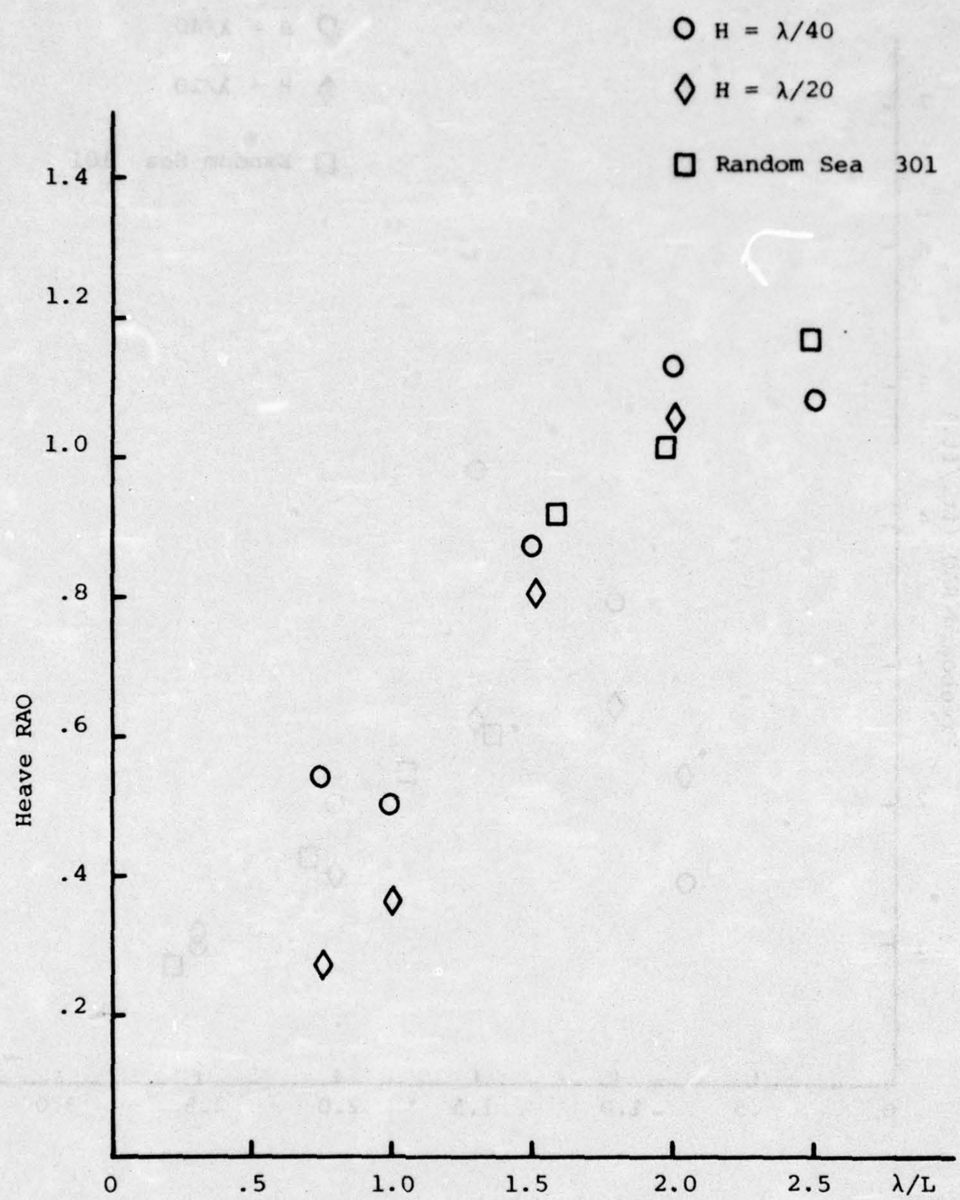

Fig. C.8 Comparison of heave RAO for runabout, head seas, for regular waves and random waves

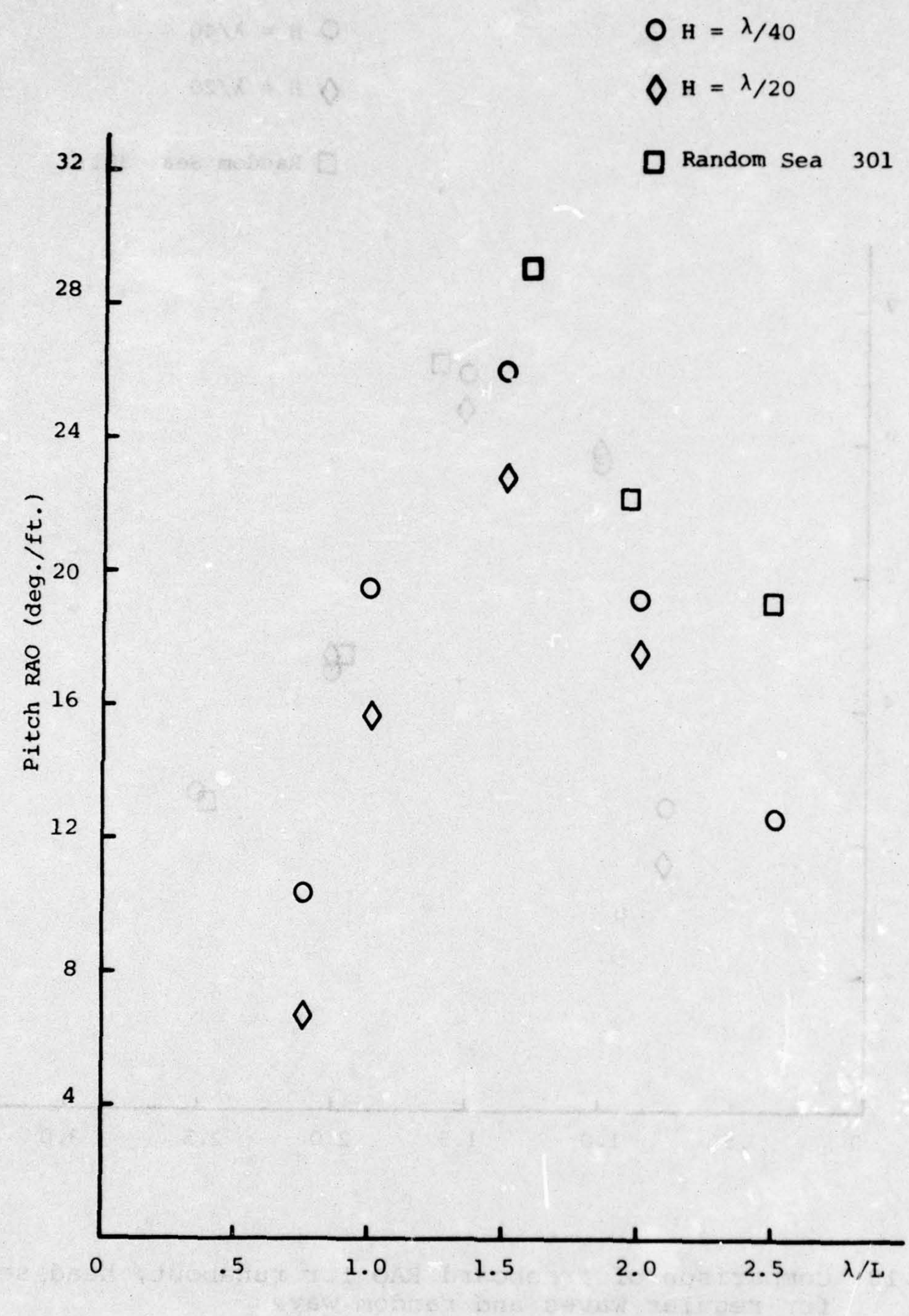

Fig. C.9 Comparison of pitch RAO for runabout, head seas, for regular waves and random waves

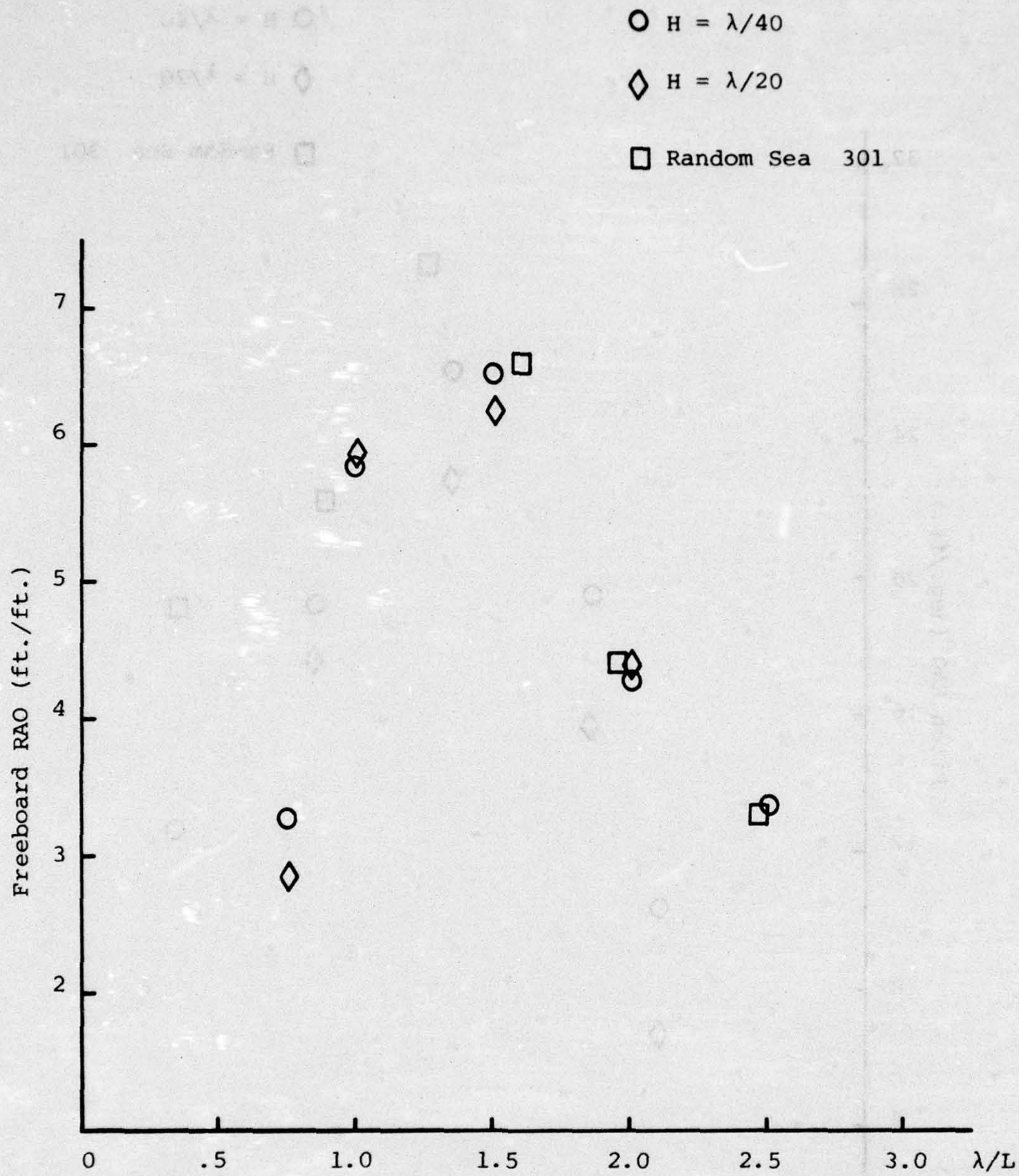

Fig. C.10 Comparison of freeboard RAO for runabout, head seas, for regular waves and random waves

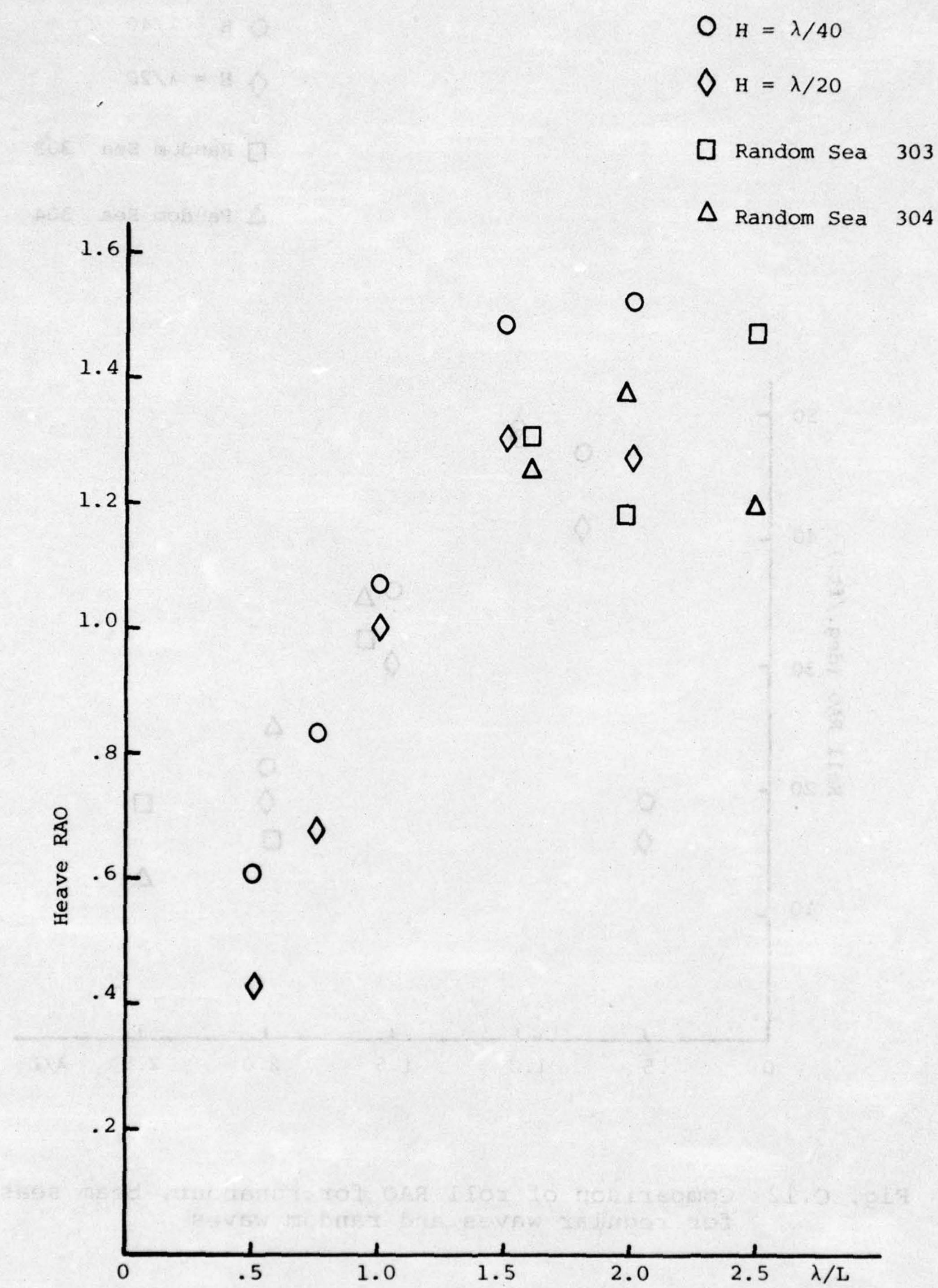

Fig. C.11 Comparison of heave RAO for runabout, beam seas, for regular waves and random waves

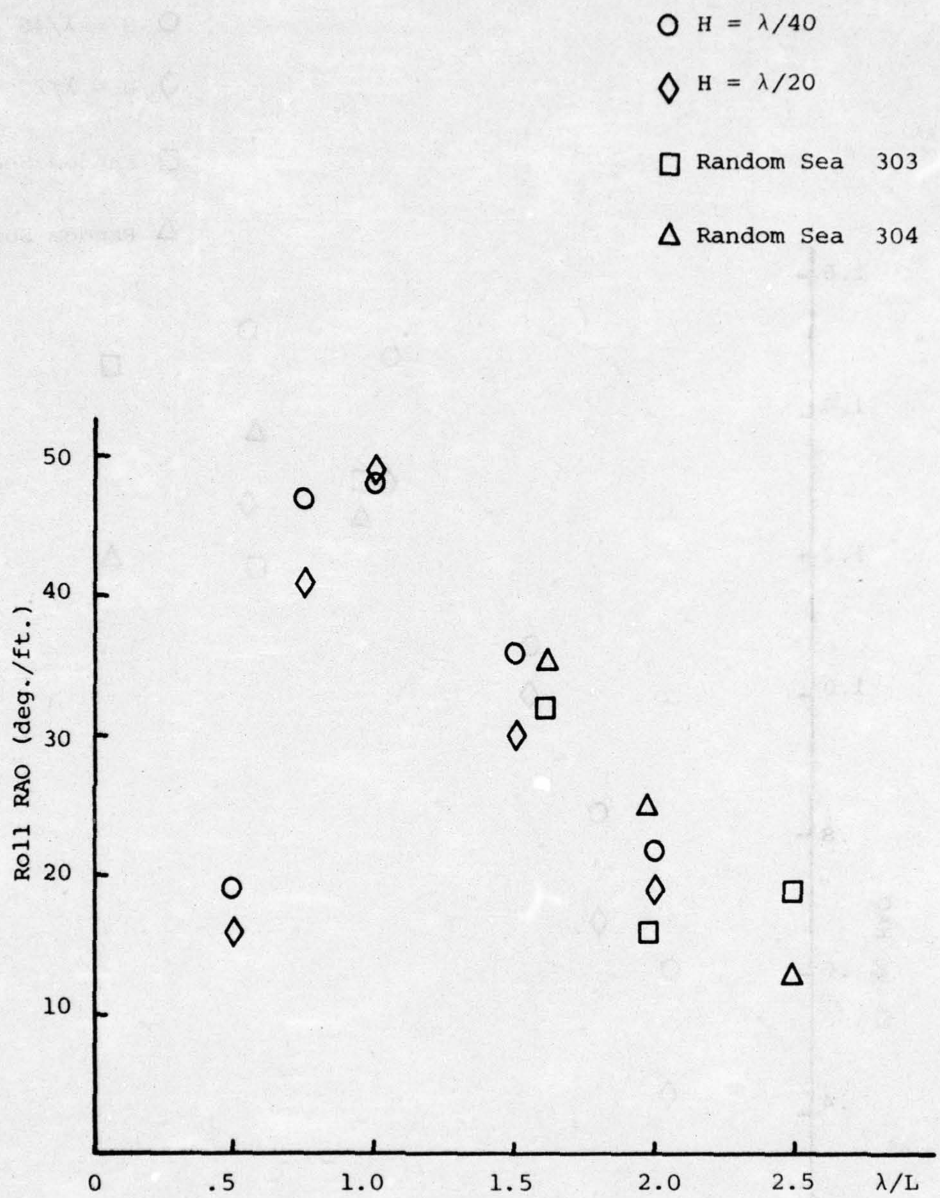

Fig. C.12 Comparison of roll RAO for runabout, beam seas, for regular waves and random waves

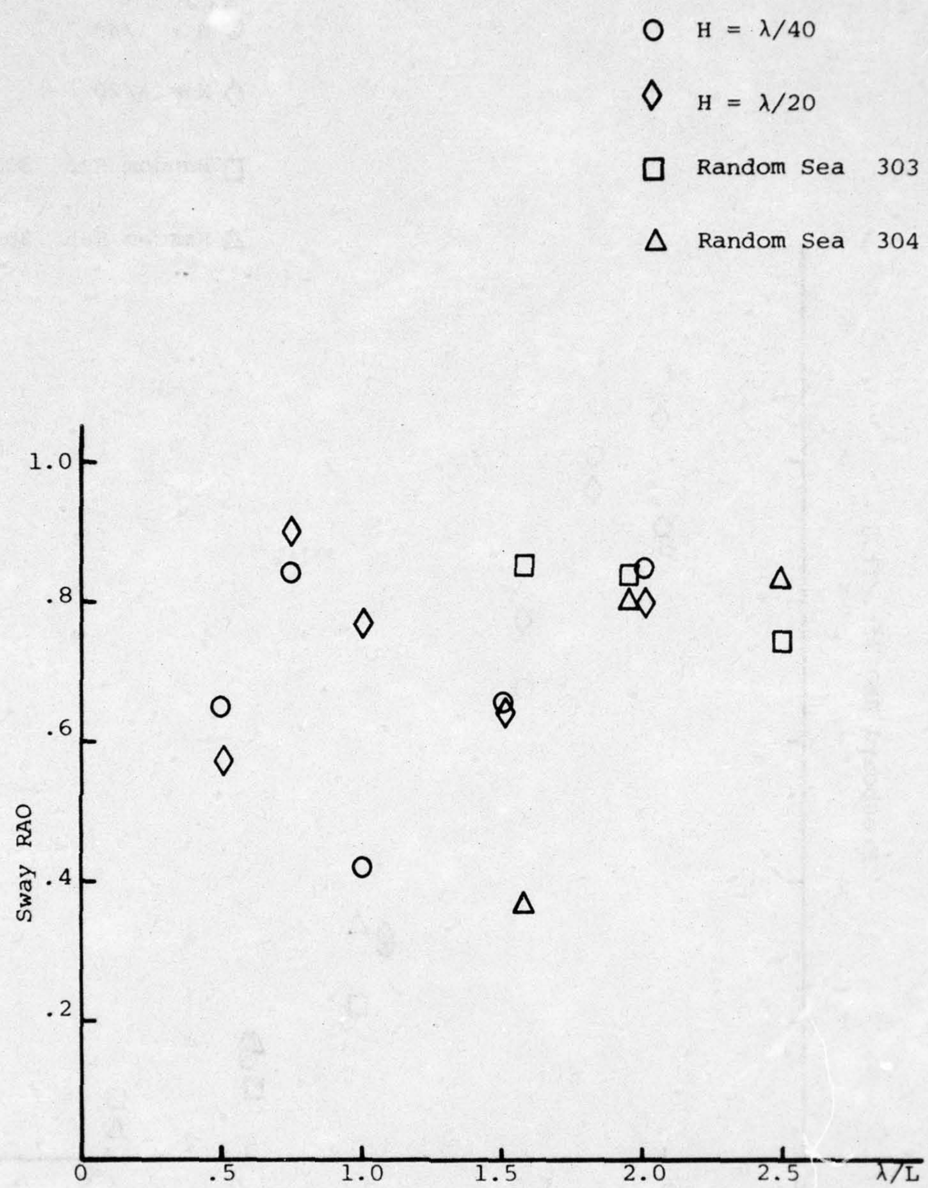

Fig. C.13 Comparison of sway RAO for runabout, beam seas, for regular waves and random waves

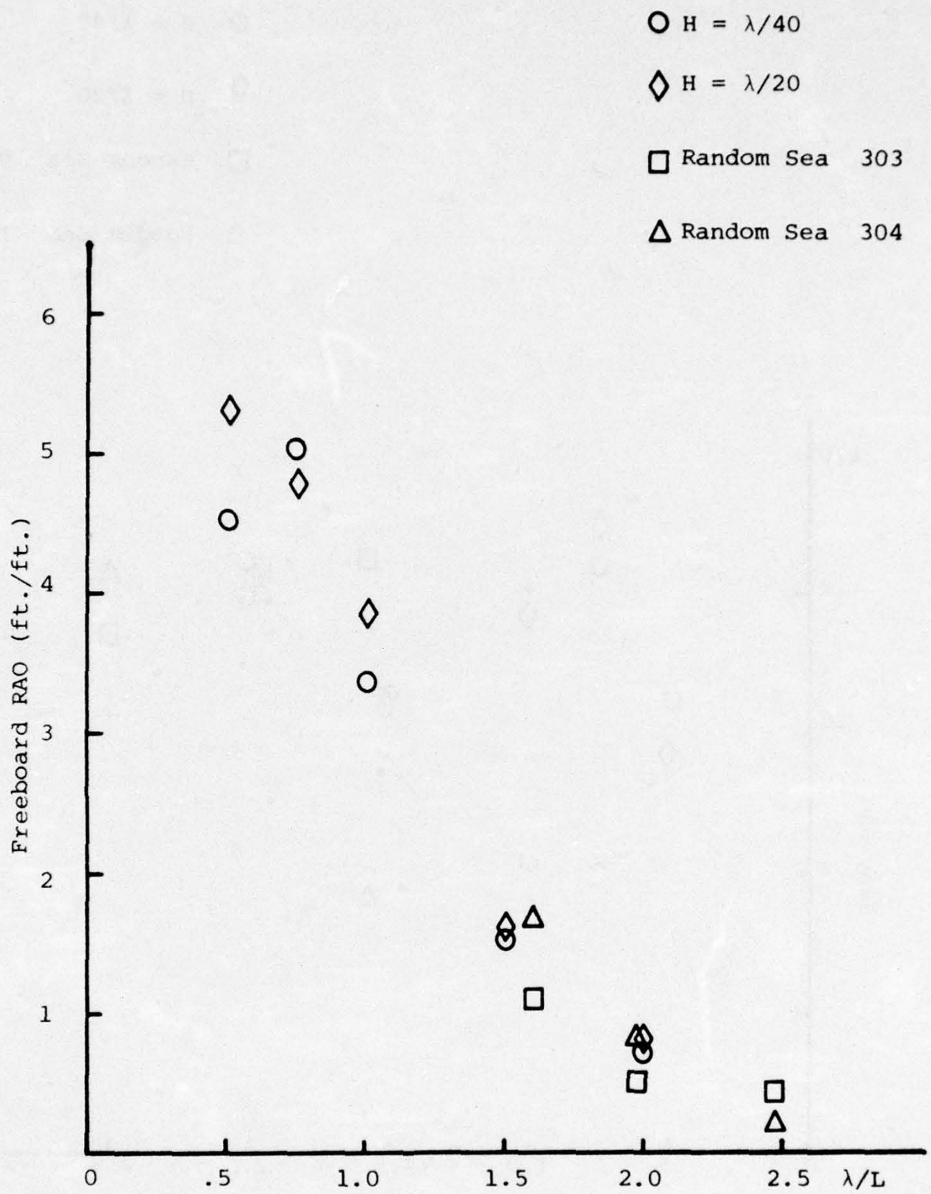

Fig. C.14 Comparison of gunwale freeboard RAO for runabout, beam seas, for regular waves and random waves

TABLE C-1

Phase Angles of Jon Boat (Load Condition 2) in Regular Waves

Wave** Height	Wave Period sec.	Heading	Phase Angle*, deg. Heave	Pitch	Roll	Freeboard***
1	1.2	Bow	- 0.8	-116.7	-	-179.5
1	1.4	Bow	14.2	-166.0	-	-148.6
1	1.7	Bow	22.3	127.4	-	170.1
1	2.0	Bow	- 6.7	91.1	-	139.7
1	2.2	Bow	- 32.1	67.6	-	124.5
2	1.2	Bow	- 97.9	119.1	-	111.3
2	1.4	Bow	- 22.2	153.5	-	180.0
2	1.7	Bow	9.1	113.2	-	146.4
2	2.0	Bow	5.9	97.6	-	132.0
2	2.2	Bow	3.6	96.9	-	128.4
1	1.2	Port	-151.1	107.4	- 92.1	70.1
1	1.4	Port	99.6	97.2	104.4	- 42.2
1	1.7	Port	- 15.5	- 76.7	- 72.2	-130.3
1	1.96	Port	- 25.9	-107.2	-100.1	112.1
1	.98	Port	- 45.4	-120.9	-111.6	175.9
2	1.2	Port	- 62.7	- 19.6	- 21.3	178.7
2	1.38	Port	29.5	79.9	33.1	- 91.3
2	1.7	Port	- 17.9	- 55.8	- 71.2	149.0
2	1.96	Port	- 44.0	- 85.9	-109.1	87.0
2	.98	Port	-174.1	-140.0	-114.3	-126.5

*Positive phase angle denotes a lag with respect to the wave c.g.

** 1 → wave height/wave length = 1/40
   2 → wave height/wave length = 1/20

*** Probe location:

Bow → x = 6.1825 ft., y = 0

Port → x = 0, y = -1.979 ft.

TABLE C-2

Phase Angles of Runabout (Load Condition 3) in Regular Waves

Wave** Height	Wave Period sec.	Heading	Phase Angles*, deg. Heave	Pitch	Roll	Freeboard***
1	1.34	Bow	- 68.3	128.3	-	119.1
1	1.55	Bow	- 12.1	-171.1	-	168.1
1	1.90	Bow	3.1	124.8	-	159.3
1	2.19	Bow	- 5.2	109.3	-	138.7
1	2.46	Bow	- 17.1	89.3	-	138.9
2	1.34	Bow	52.7	-122.7	-	-164.6
2	1.55	Bow	-166.4	- 28.8	-	- 18.8
2	1.90	Bow	11.7	134.0	-	166.0
2	2.19	Bow	0.7	109.4	-	140.8
2	2.46	Bow	- 10.8	99.7	-	129.5
1	1.34	Port	-103.7	- 27.6	-114.4	91.5
1	1.55	Port	-104.4	- 51.2	-131.5	64.4
1	1.90	Port	- 97.7	-109.0	-169.6	23.1
1	2.19	Port	- 60.8	-125.3	-155.2	129.1
1	1.10	Port	160.1	146.6	157.5	8.6
2	1.34	Port	- 13.4	79.4	- 4.9	-164.3
2	1.55	Port	29.2	83.0	- 7.4	-158.8
2	1.90	Port	- 70.9	- 23.2	-143.1	71.7
2	2.19	Port	- 79.2	- 68.8	-162.4	36.7
2	1.10	Port	- 62.8	53.6	- 60.7	162.0

*Positive phase angle denotes a lag with respect to the wave c.g.

** 1 → wave height/wave length = 1/40
→ wave height/wave length = 1/20

*** Probe location:

Bow → x = 8.646 ft., y = 0

Port → x = -1.292 ft., y = -3.021 ft.

APPENDIX D

COMPARISON OF RESPONSE AMPLITUDE OPERATORS,

FULL SCALE AND MODEL TESTS IN RANDOM WAVES

APPENDIX D

		Test Run
1.	Comparison of full scale and model pitch RAO, jon boat in head seas.	1
2.	Comparison of full scale and model heave acceleration RAO, jon boat in head seas.	1
3.	Comparison of full scale and model pitch RAO, jon boat in following seas.	2
4.	Comparison of full scale and model heave acceleration RAO, jon boat in following seas.	2
5.	Comparison of full scale and model heave acceleration RAO, jon boat in beam seas.	4
6.	Comparison of full scale and model sway acceleration RAO, jon boat in beam seas.	4
7.	Comparison of full scale and model roll angle RAO, jon boat in beam seas.	4
8.	Comparison of full scale and heave acceleration RAO, jon boat in head seas, (anchor at bow).	5
9.	Comparison of full scale and pitch angle RAO, jon boat in head seas (anchor at bow).	5
10.	Comparison of full scale and model sway acceleration RAO, jon boat in beam seas.	7
11.	Comparison of full scale and model heave acceleration RAO, jon boat in beam seas.	7
12.	Comparison of full scale and model roll angle RAO, jon boat in beam seas.	7
13.	Comparison of full scale and model roll angle RAO, jon boat, in beam seas.	8
14.	Comparison of full scale and model sway acceleration RAO, jon boat in beam seas.	8
15.	Comparison of full scale and model heave acceleration RAO, jon boat in beam seas.	8
16.	Comparison of full scale and model heave acceleration RAO, jon boat in head seas.	14
17.	Comparison of full scale and model pitch angle RAO, jon boat in head seas.	14
18.	Comparison of full scale and model pitch angle RAO, jon boat in following seas.	15
19.	Comparison of full scale and model heave acceleration RAO, jon boat in following seas.	15

D

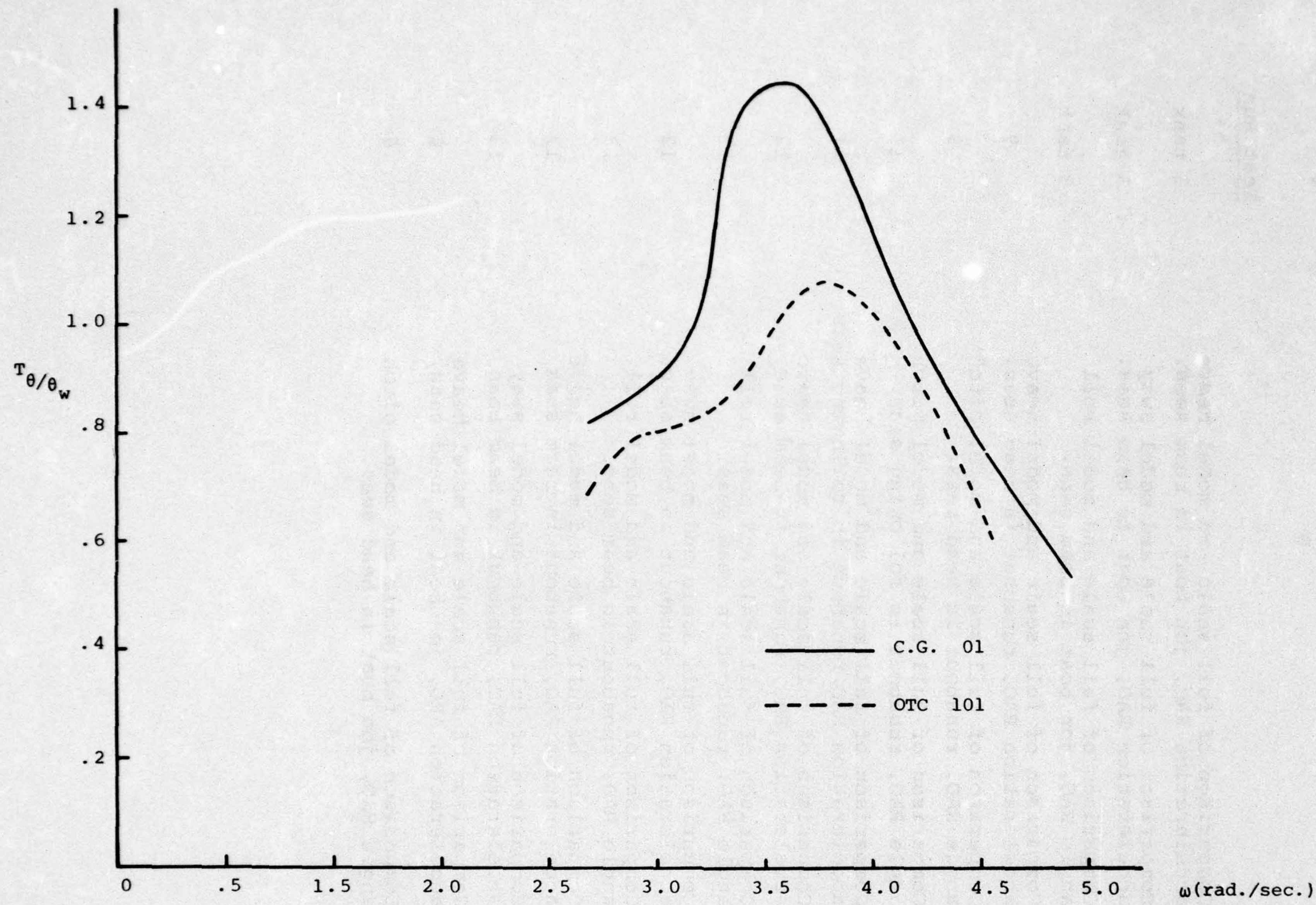

Fig. D.1 Comparison of full scale and model pitch RAO, jon boat in head seas, Test No. 1

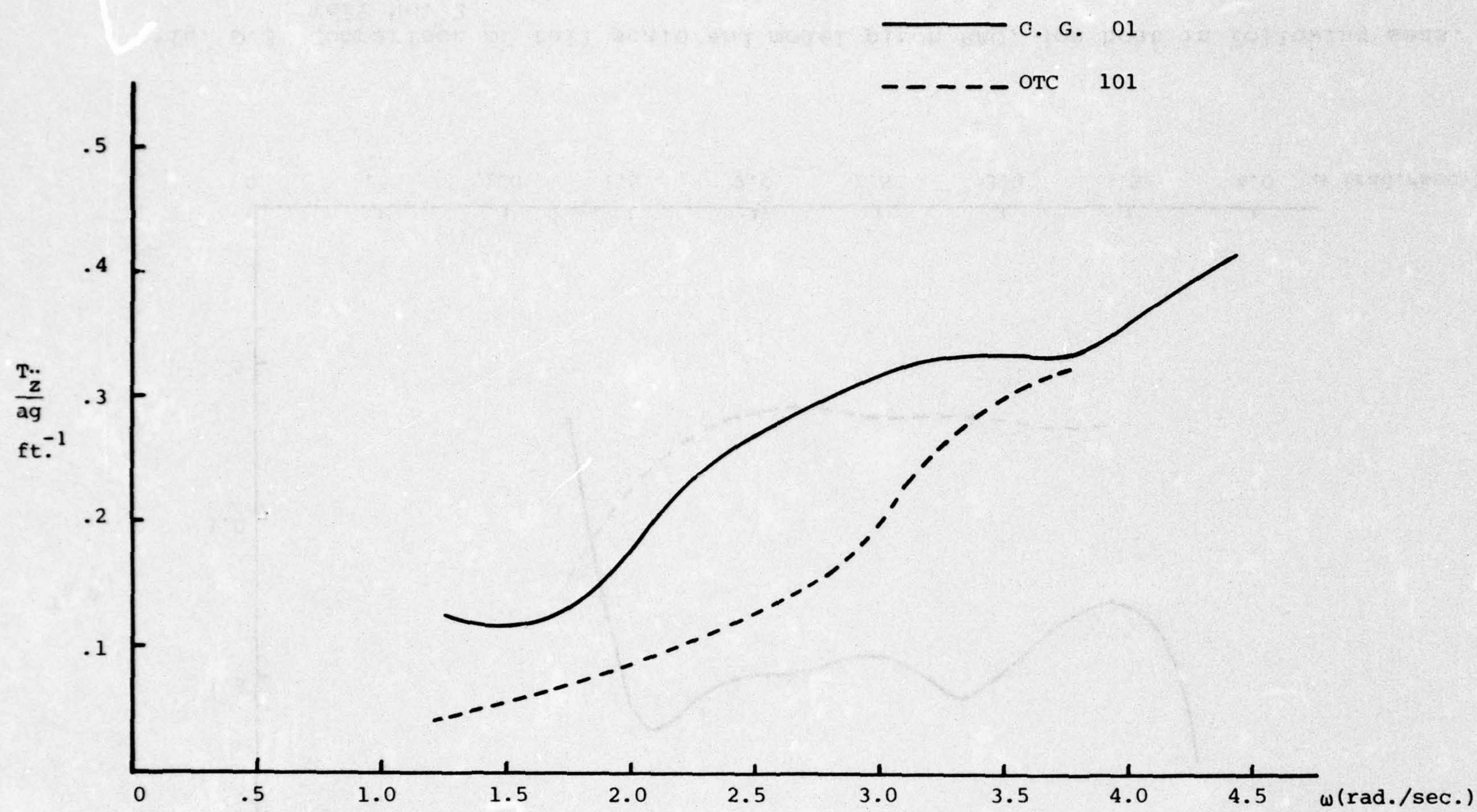

Fig. D.2 Comparison of full scale and model heave acceleration RAO, jon boat in head seas, Test No. 1

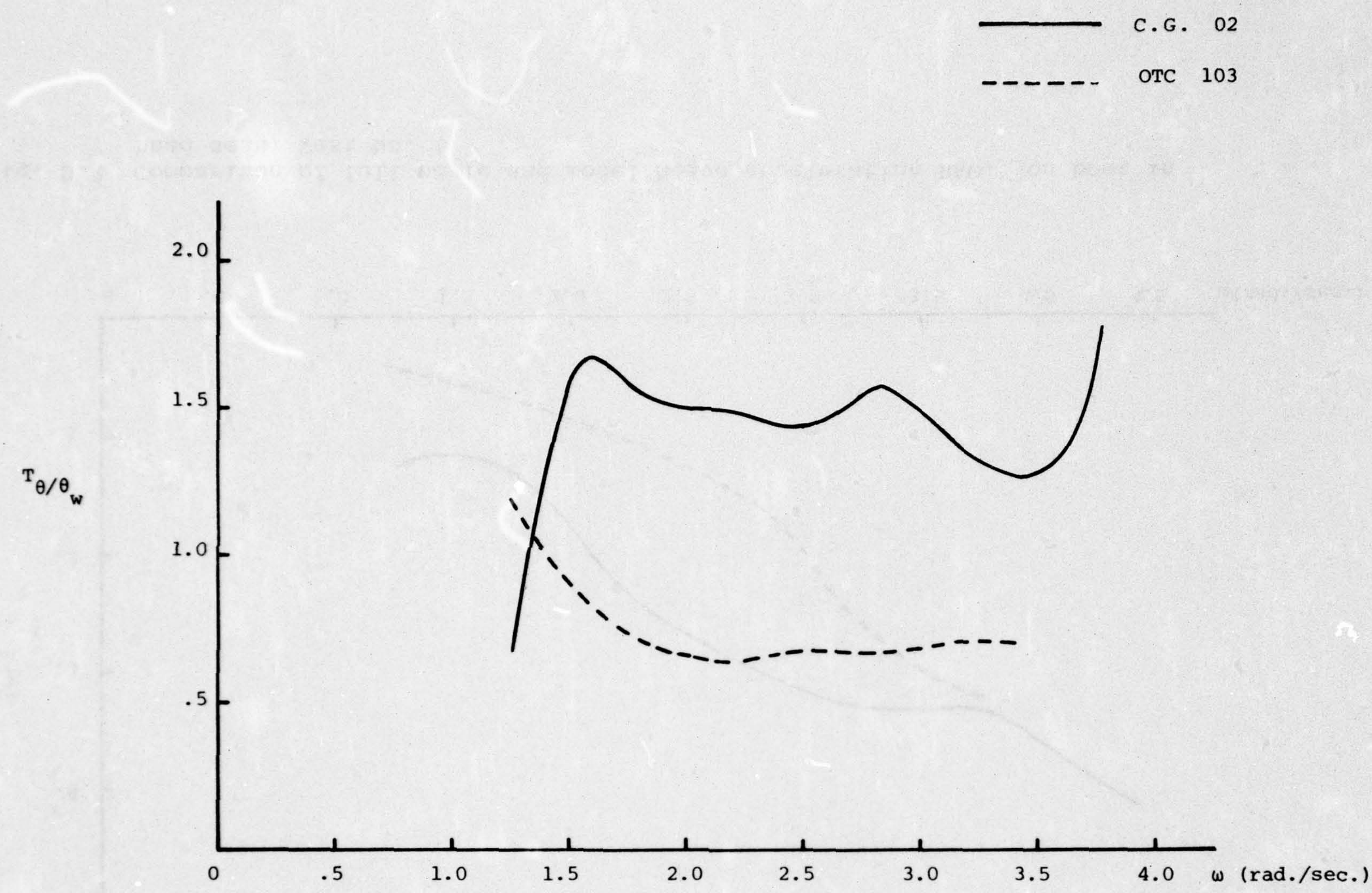

Fig. D.3 Comparison of full scale and model pitch RAO, jon boat in following seas, Test No. 2

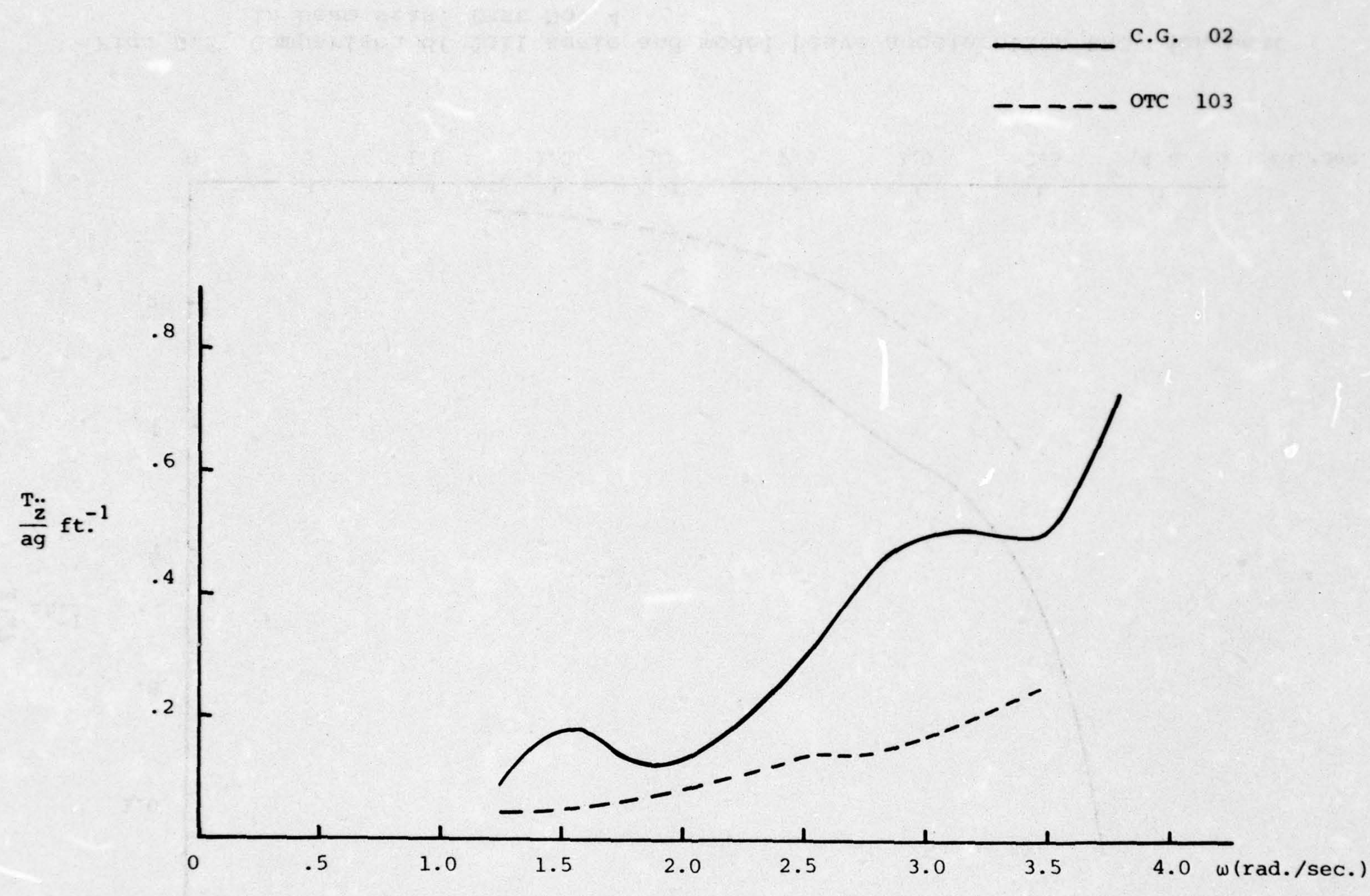

Fig. D.4 Comparison of full scale and model heave acceleration RAO, jon boat in following seas, Test No. 2

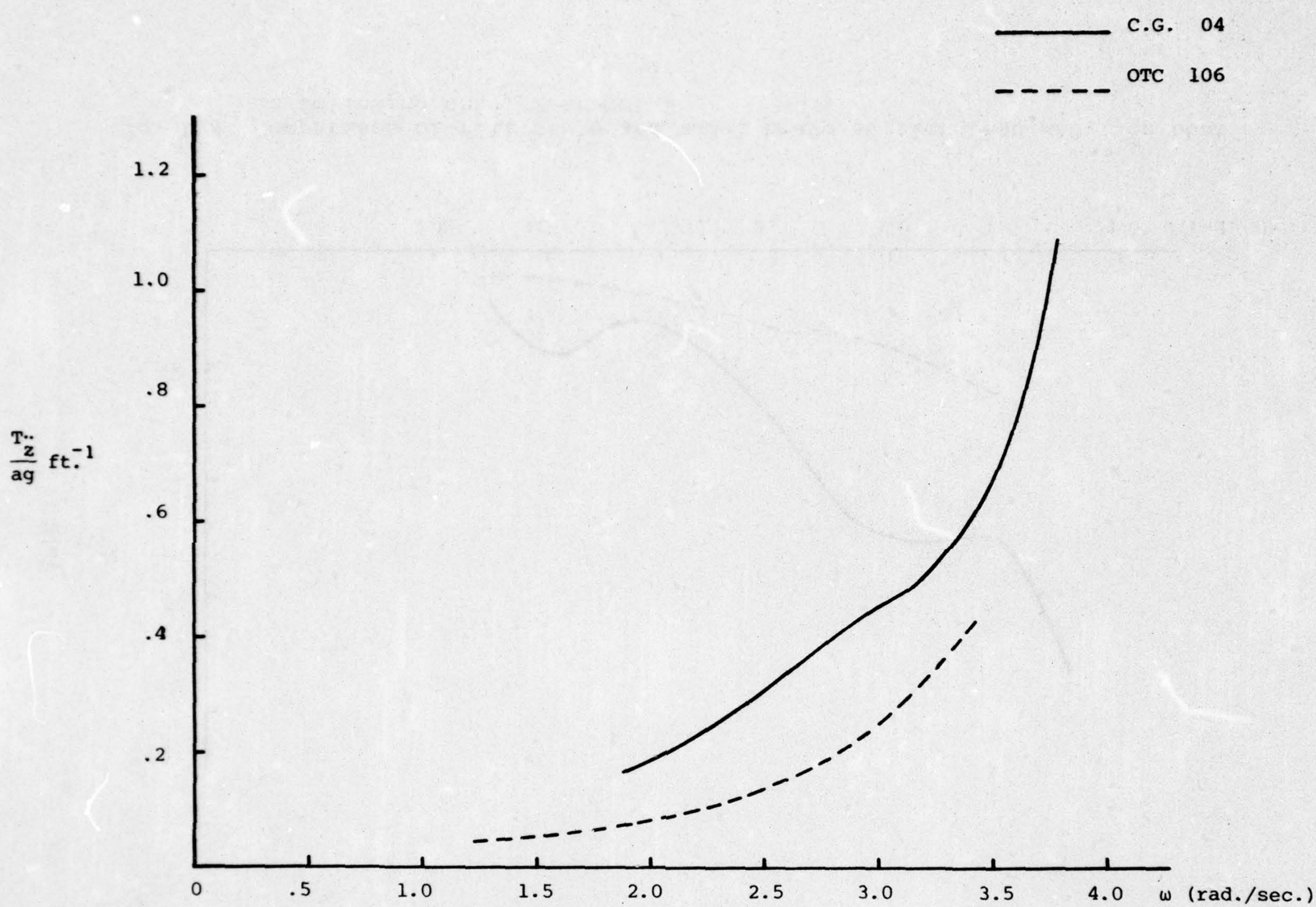

Fig. D.5 Comparison of full scale and model heave acceleration RAO, jon boat in beam seas, Test No. 4

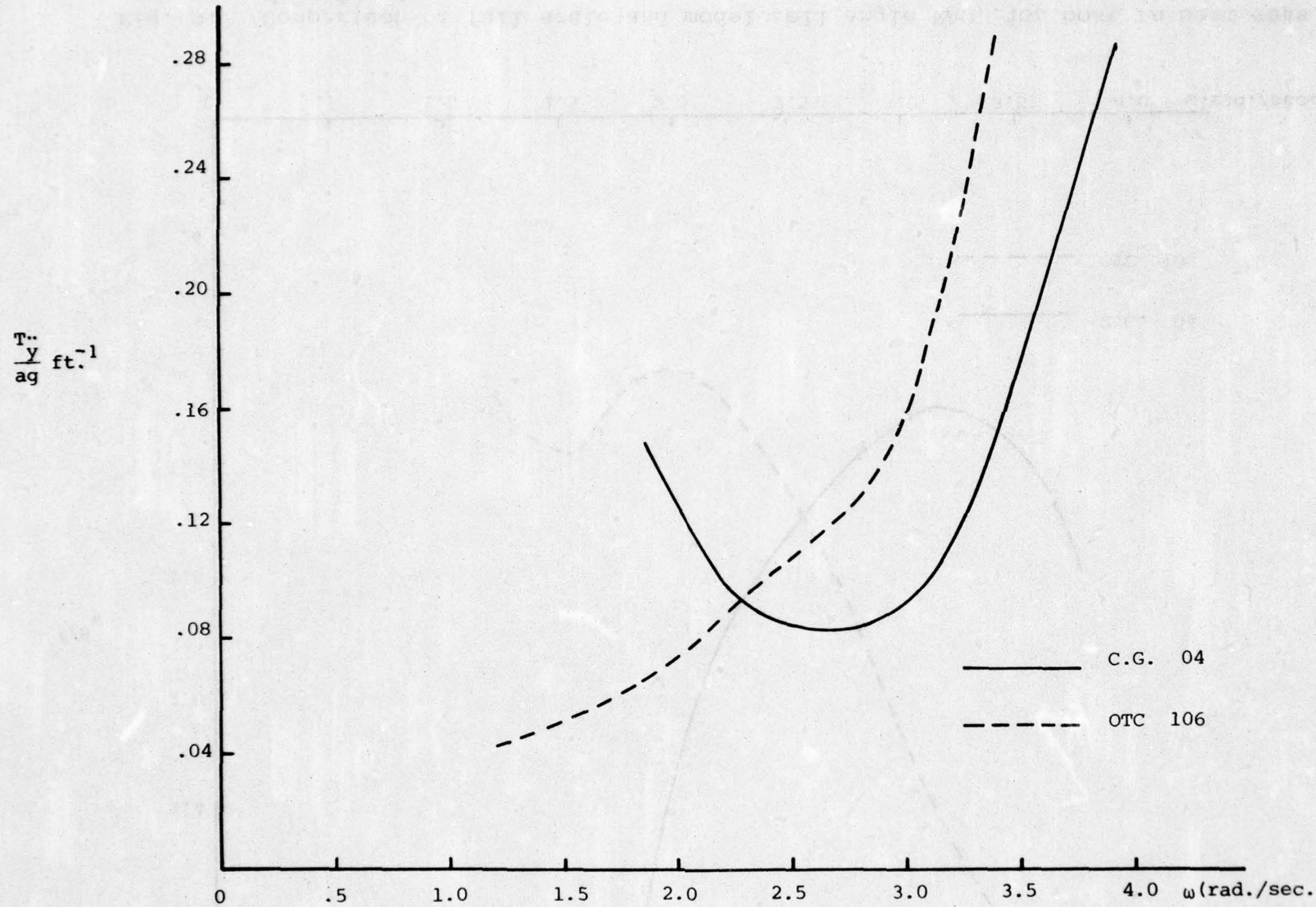

Fig. D.6 Comparison of full scale and model sway acceleration RAO, jon boat in beam seas, Test No. 4

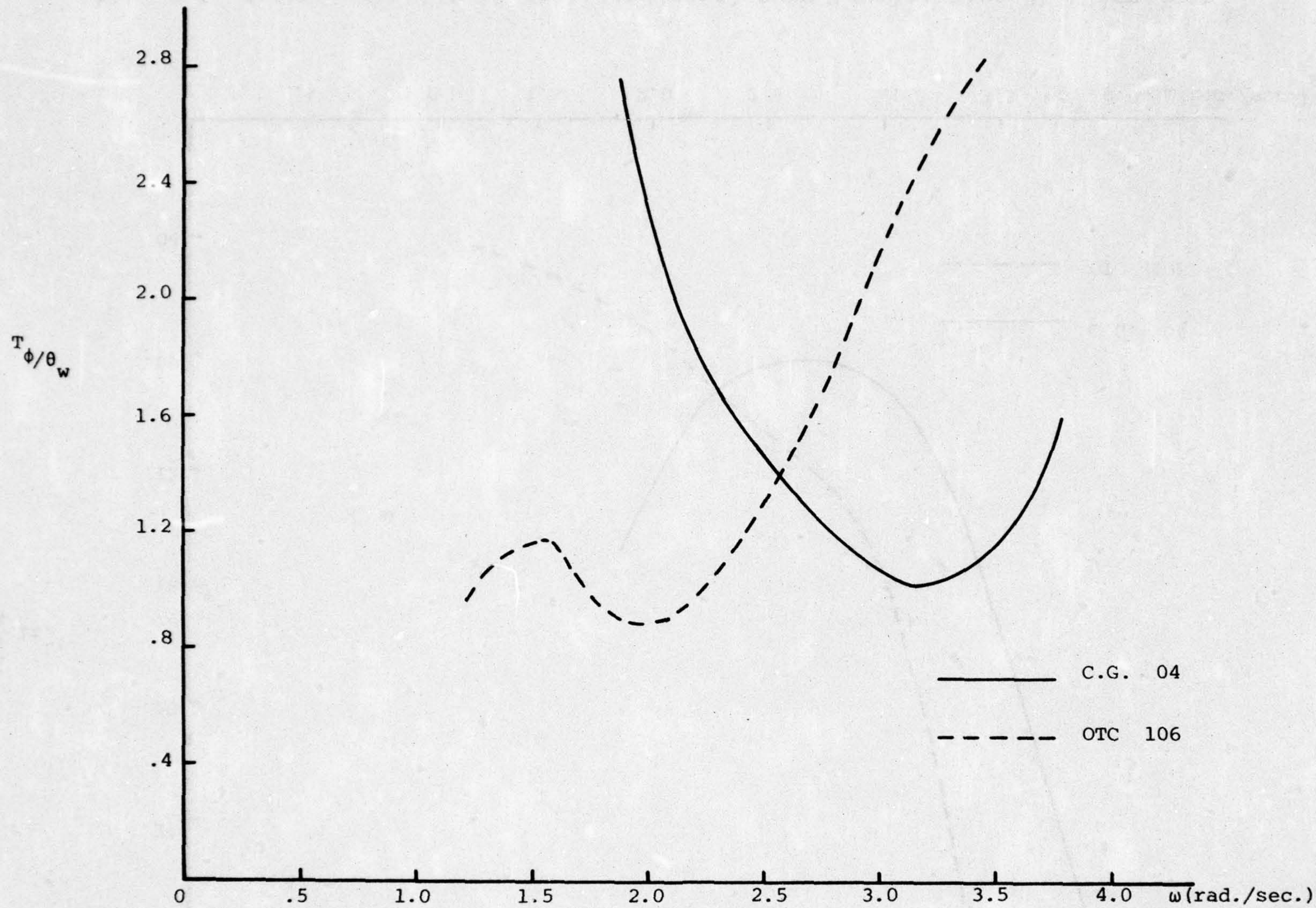

Fig. D.7 Comparison of full scale and model roll angle RAO, jon boat in beam seas, Test No. 4

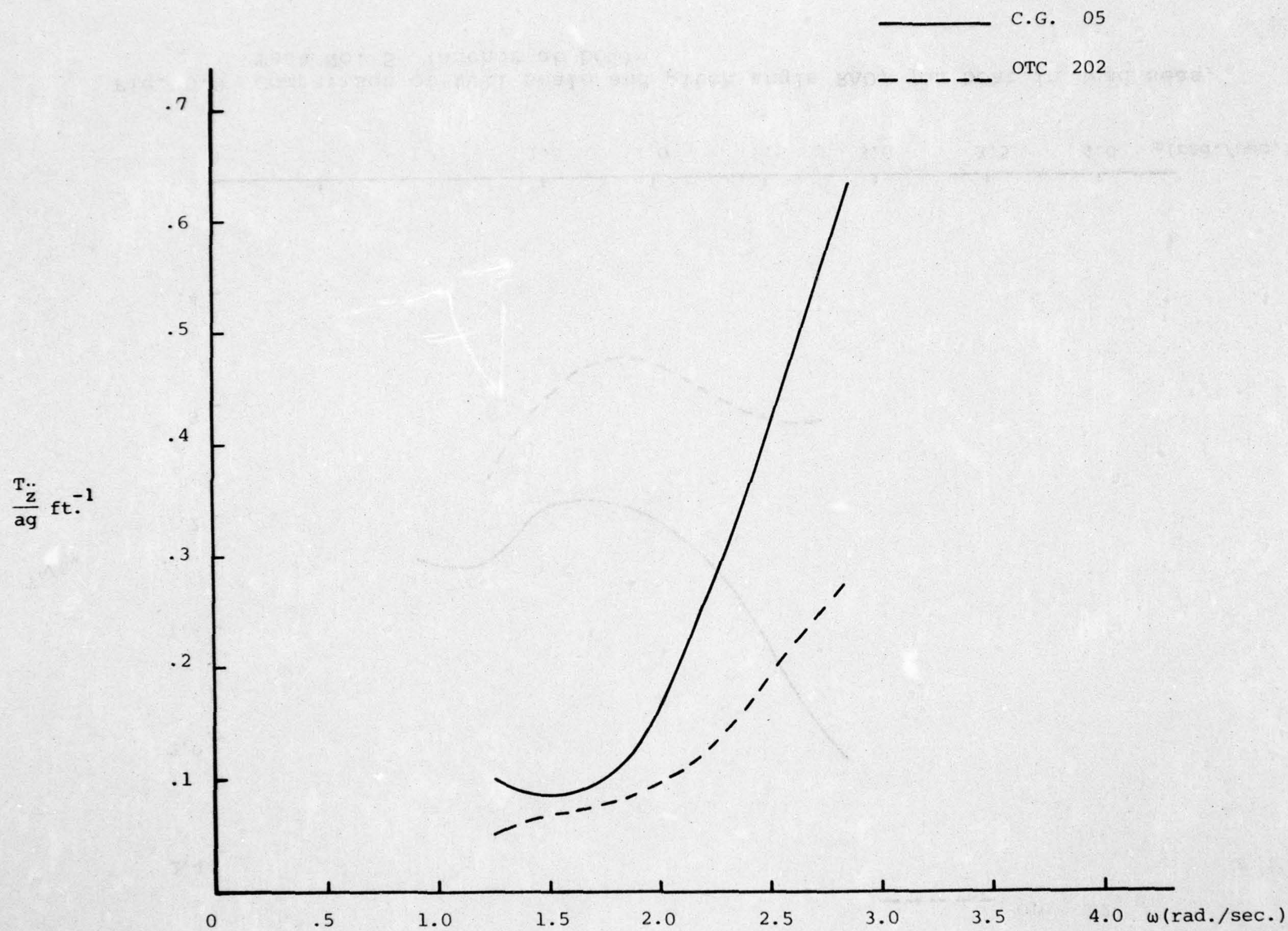

Fig. D.8 Comparison of full scale and heave acceleration RAO, jon boat in head seas, Test No. 5 (anchor at bow)

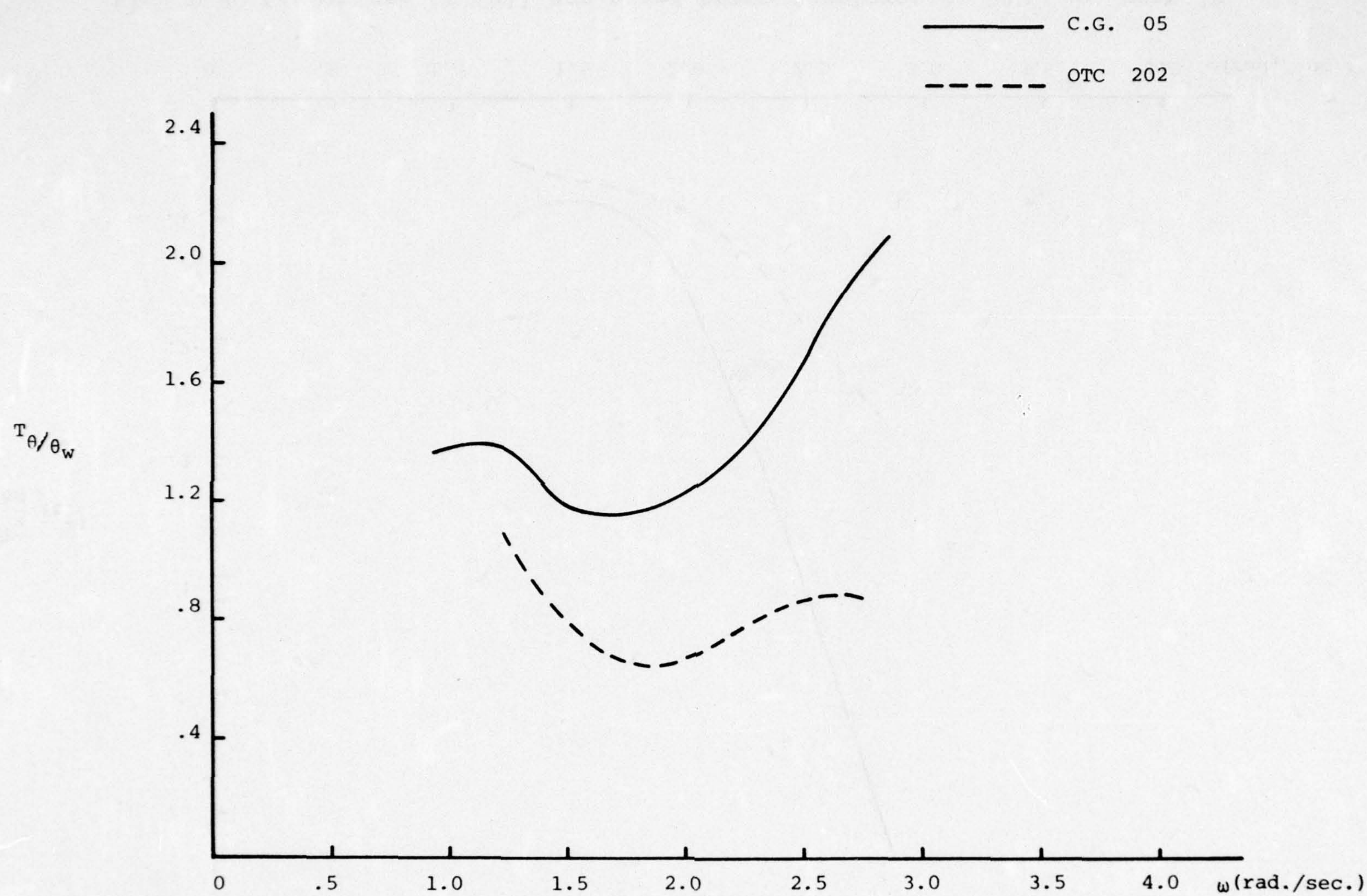

Fig. D.9 Comparison of full scale and pitch angle RAO, jon boat in head seas, Test No. 5 (anchor at bow)

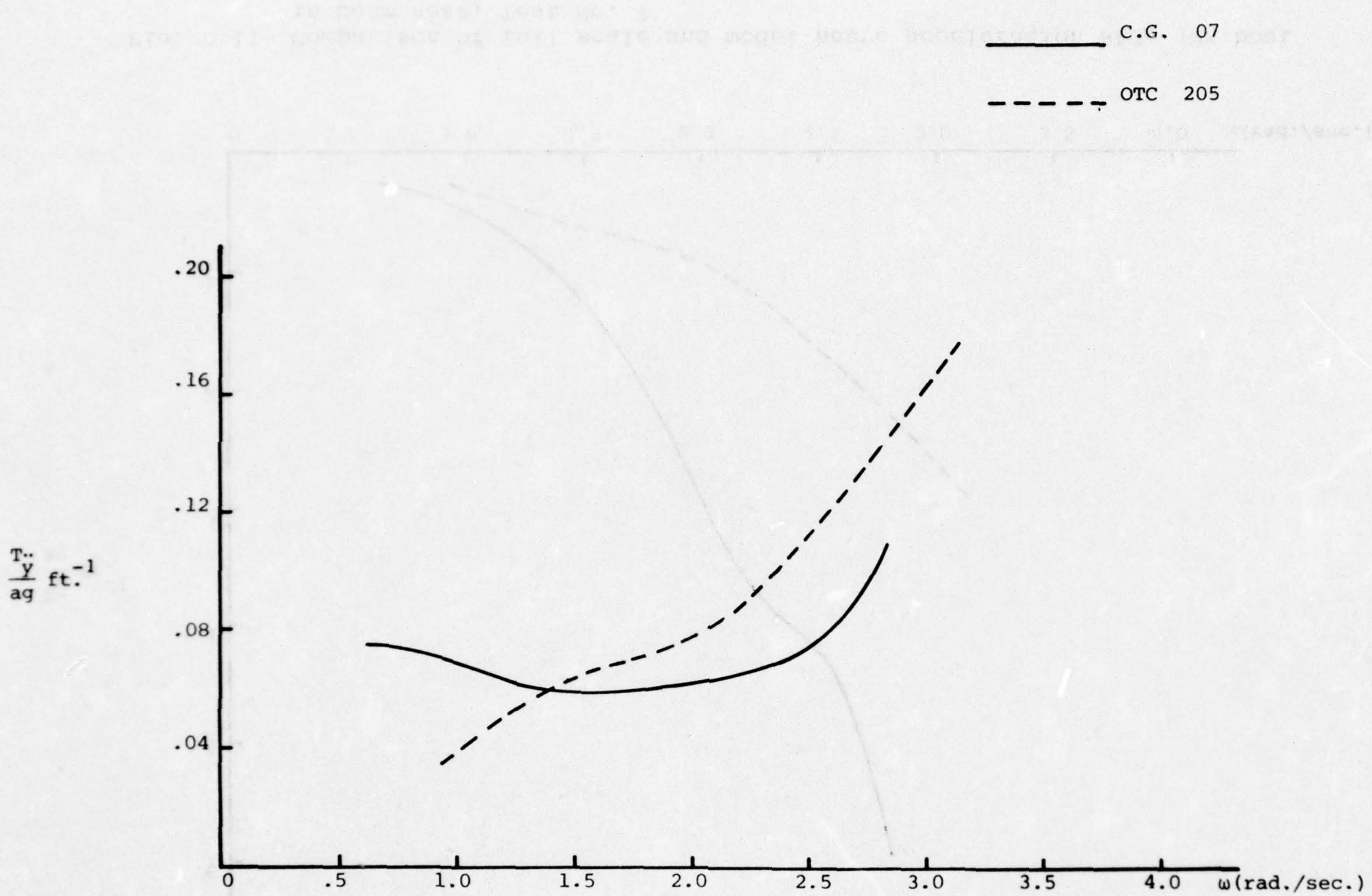

Fig. D.10 Comparison of full scale and model sway acceleration RAO, jon boat in beam seas, Test No. 7

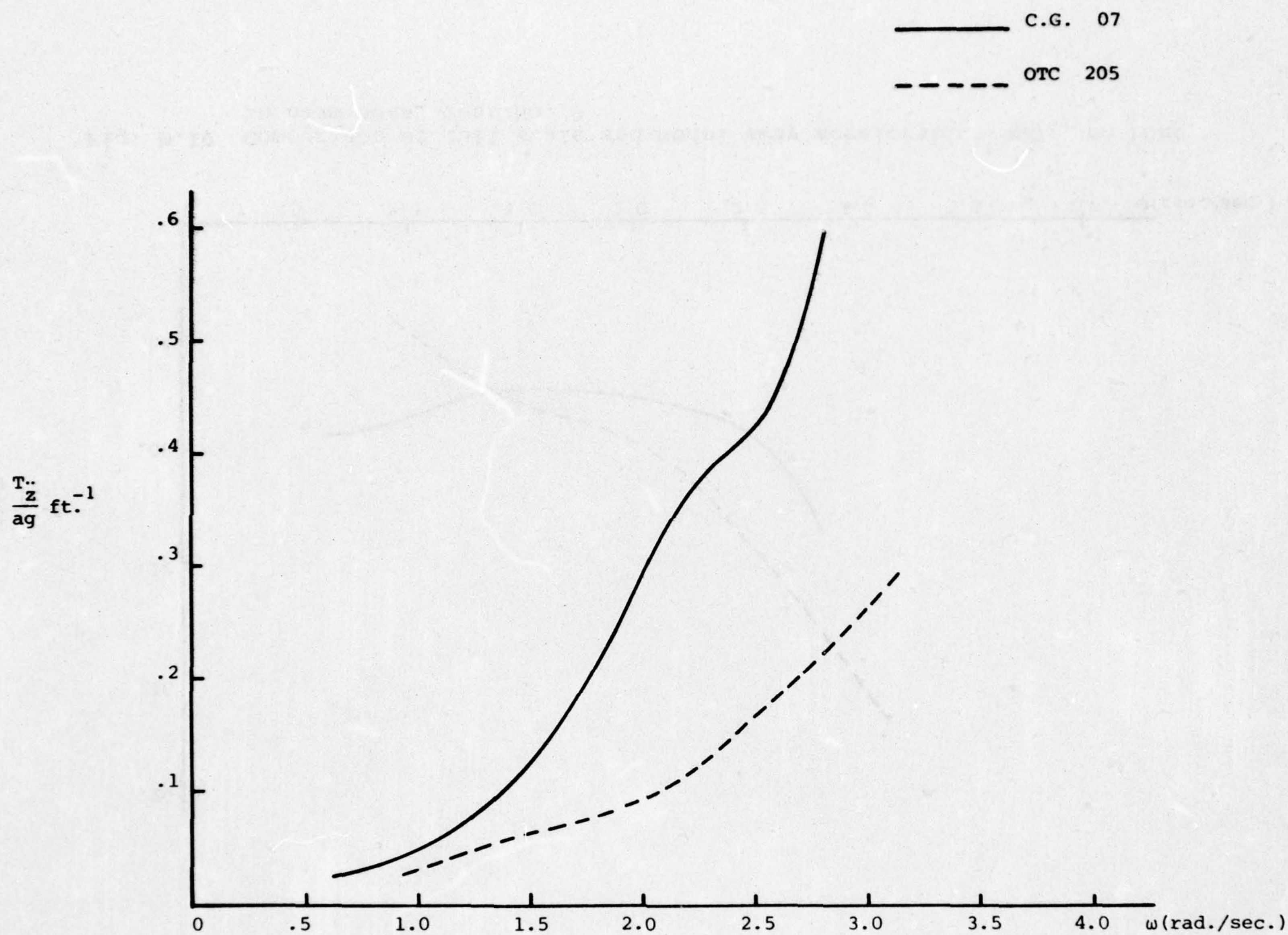

Fig. D.11 Comparison of full scale and model heave acceleration RAO, jon boat in beam seas, Test No. 7

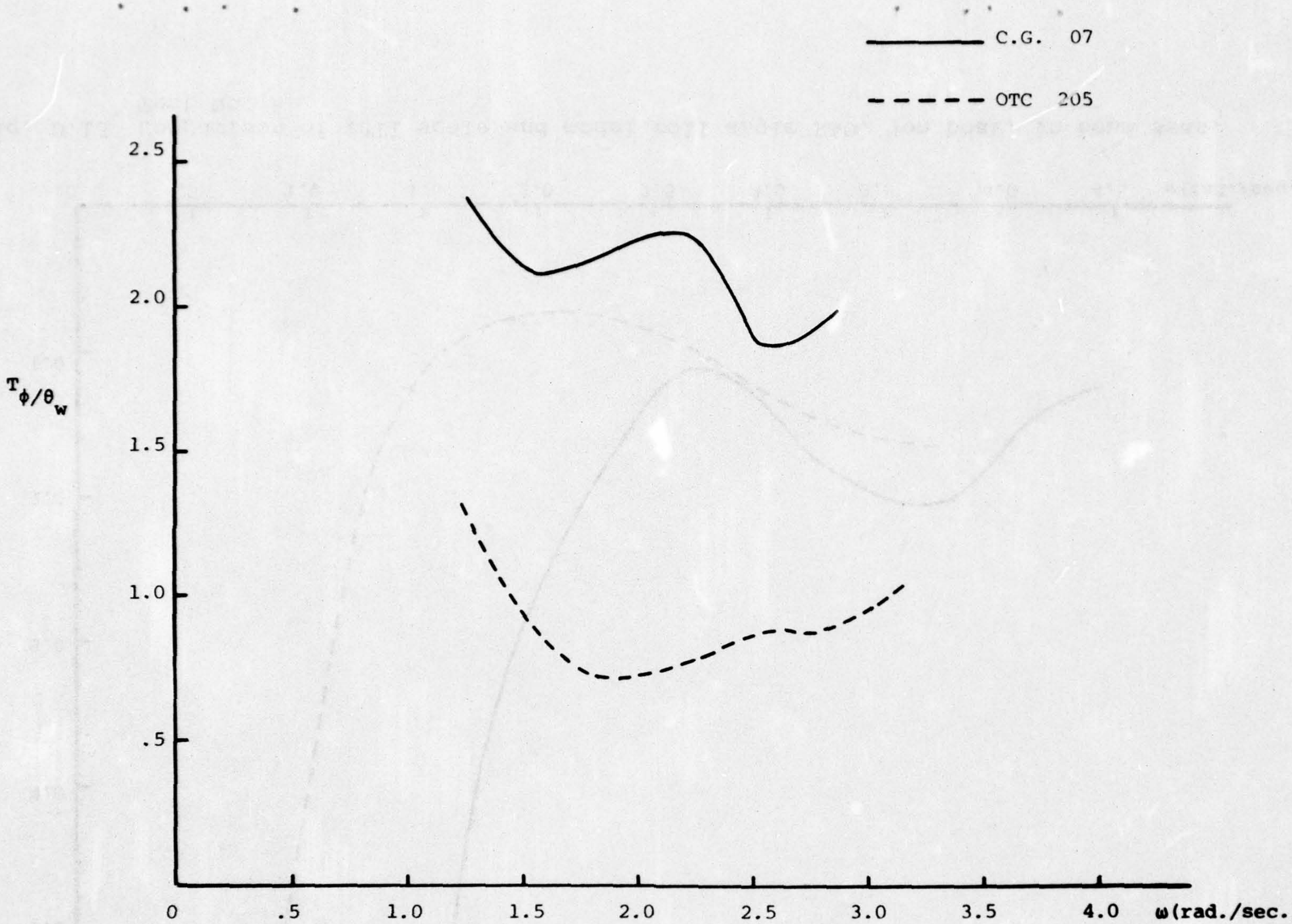

Fig. D.12 Comparison of full scale and model roll angle RAO, jon boat in beam seas, Test No. 7

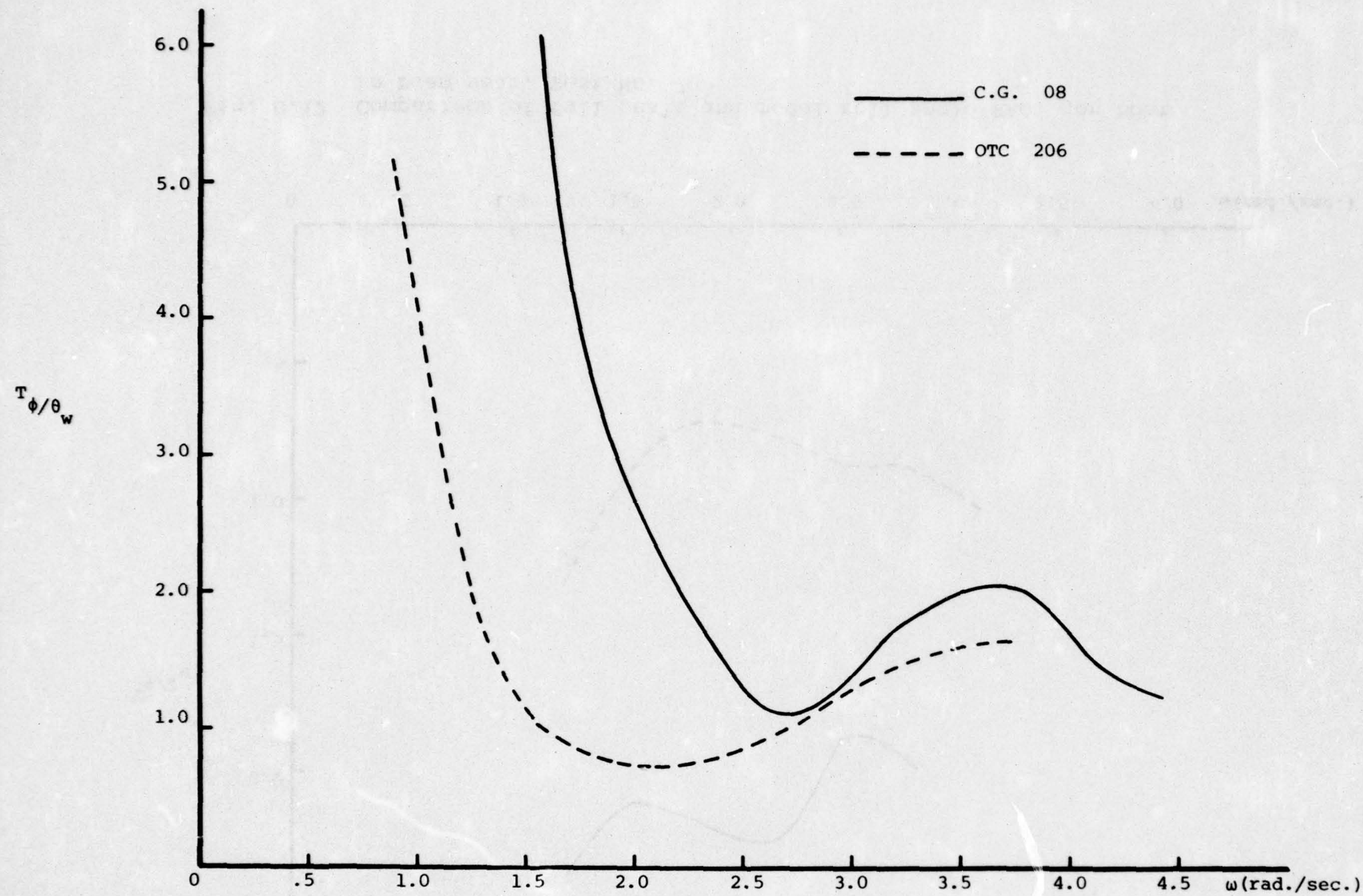

Fig. D.13 Comparison of full scale and model roll angle RAO, jon boat, in beam seas, Test No. 8

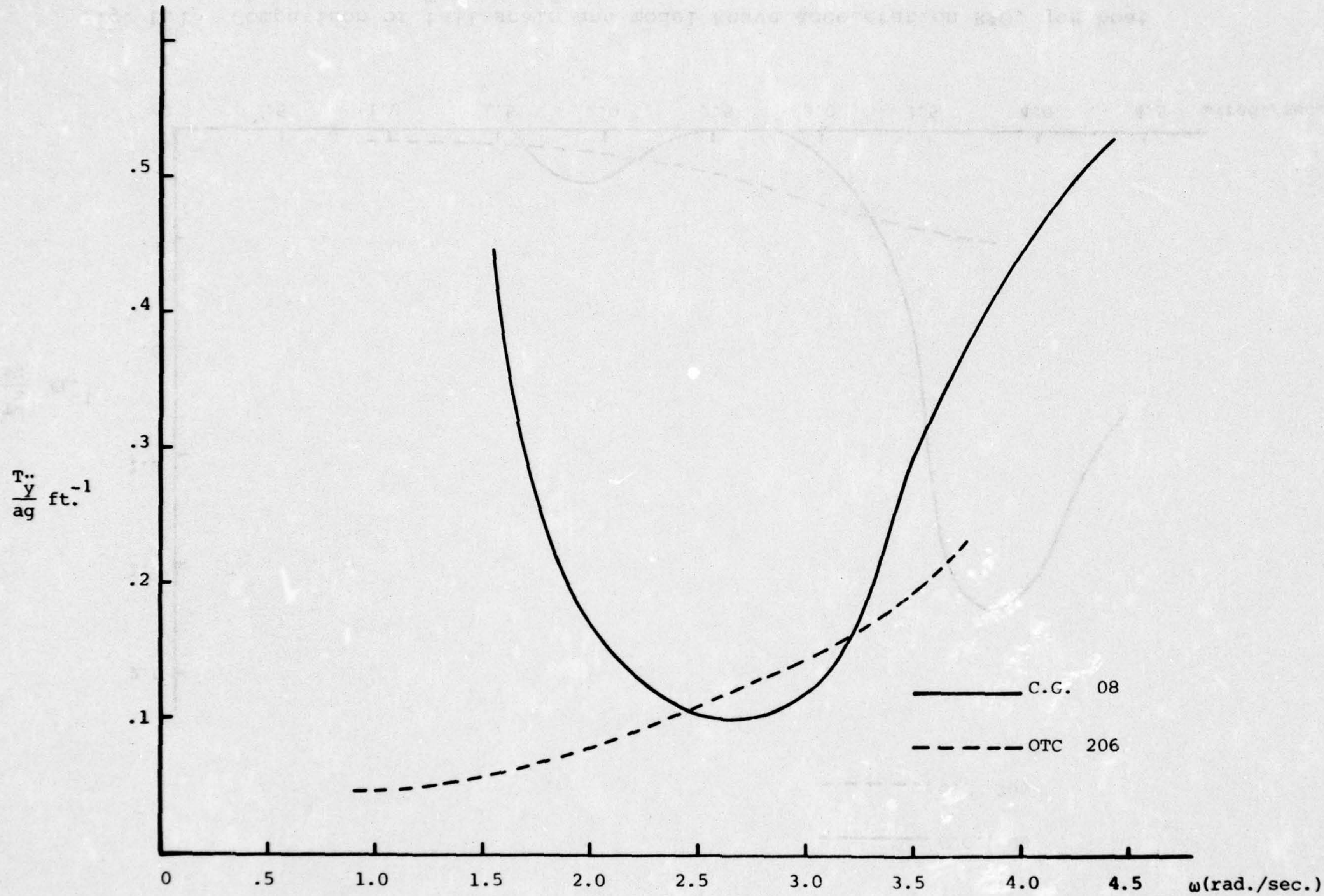

Fig. D.14 Comparison of full scale and model sway acceleration RAO, jon boat in beam seas, Test No. 8

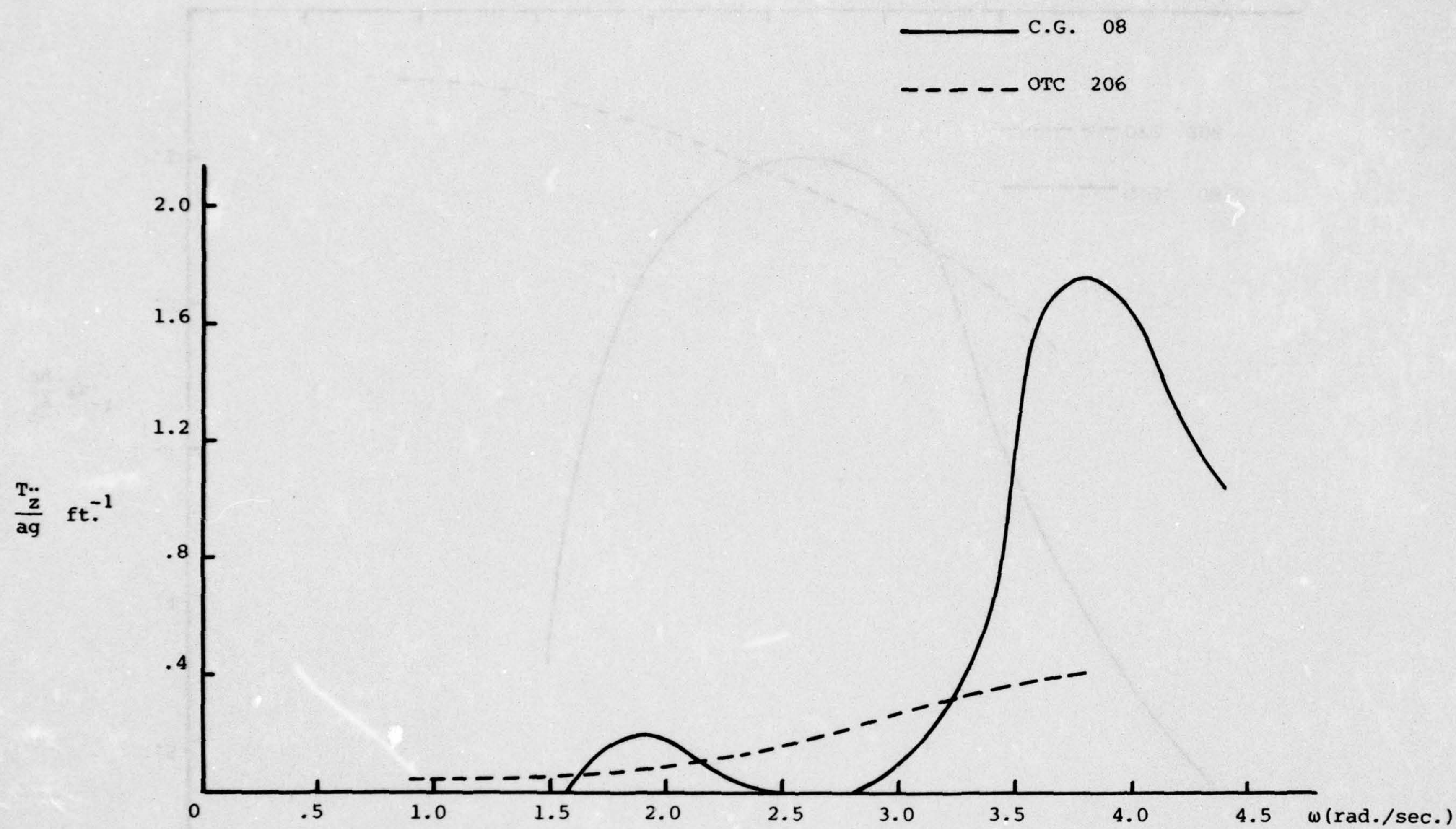

Fig. D.15 Comparison of full scale and model heave acceleration RAO, jon boat in beam seas, Test No. 8

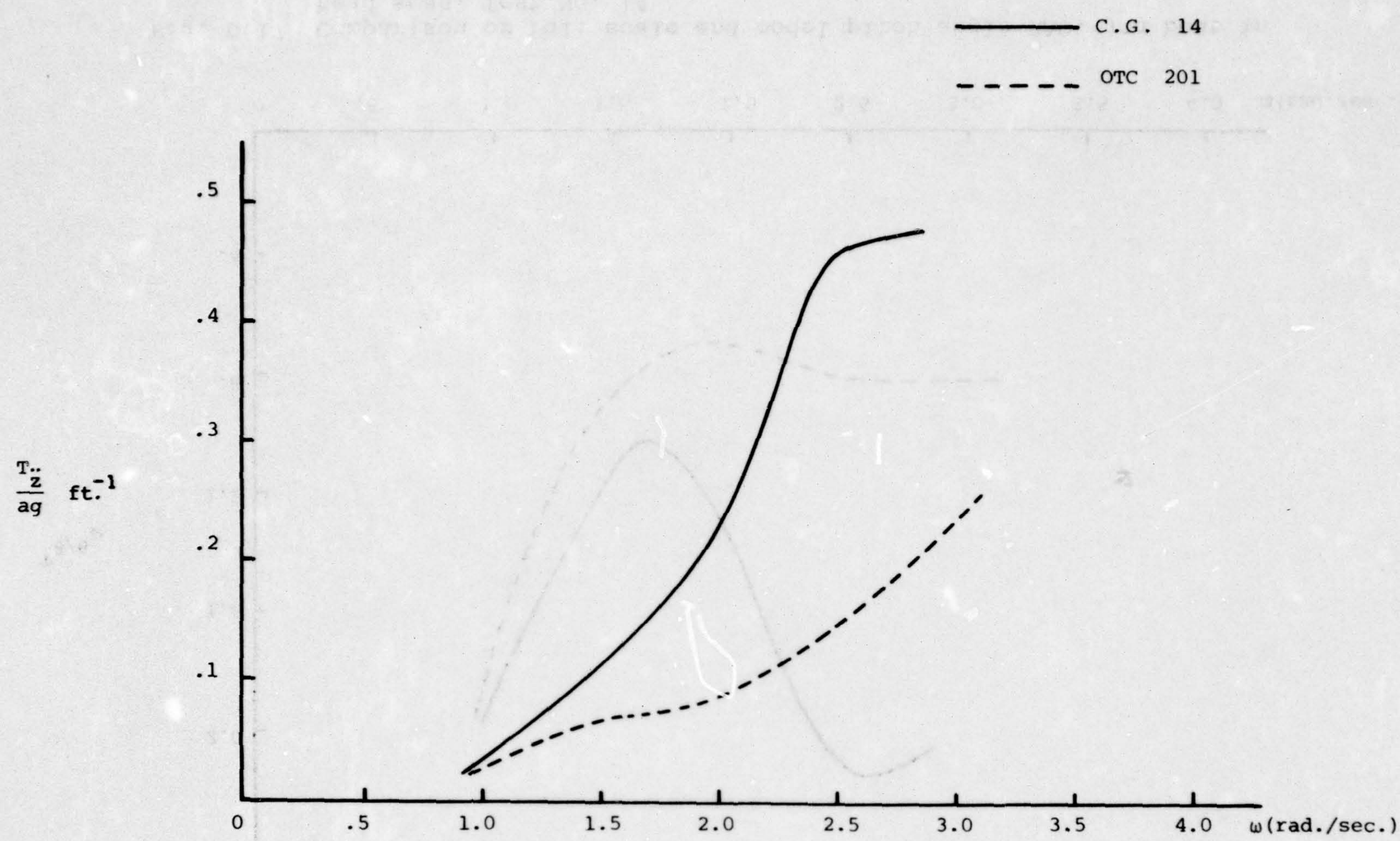

Fig. D.16 Comparison of full scale and model heave acceleration RAO, jon boat in head seas, Test No. 14

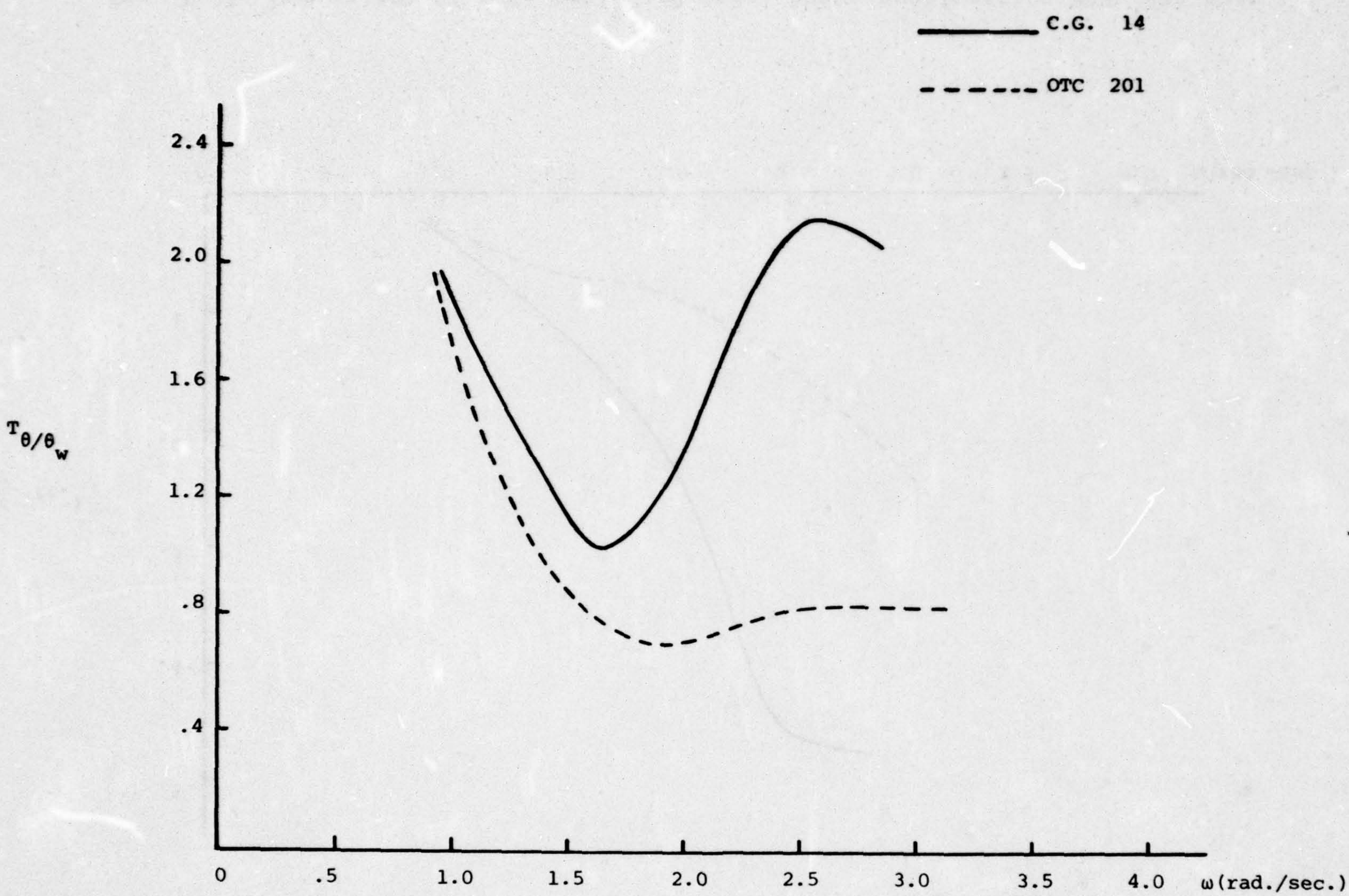

Fig. D.17 Comparison of full scale and model pitch angle RAO, jon boat in head seas, Test No. 14

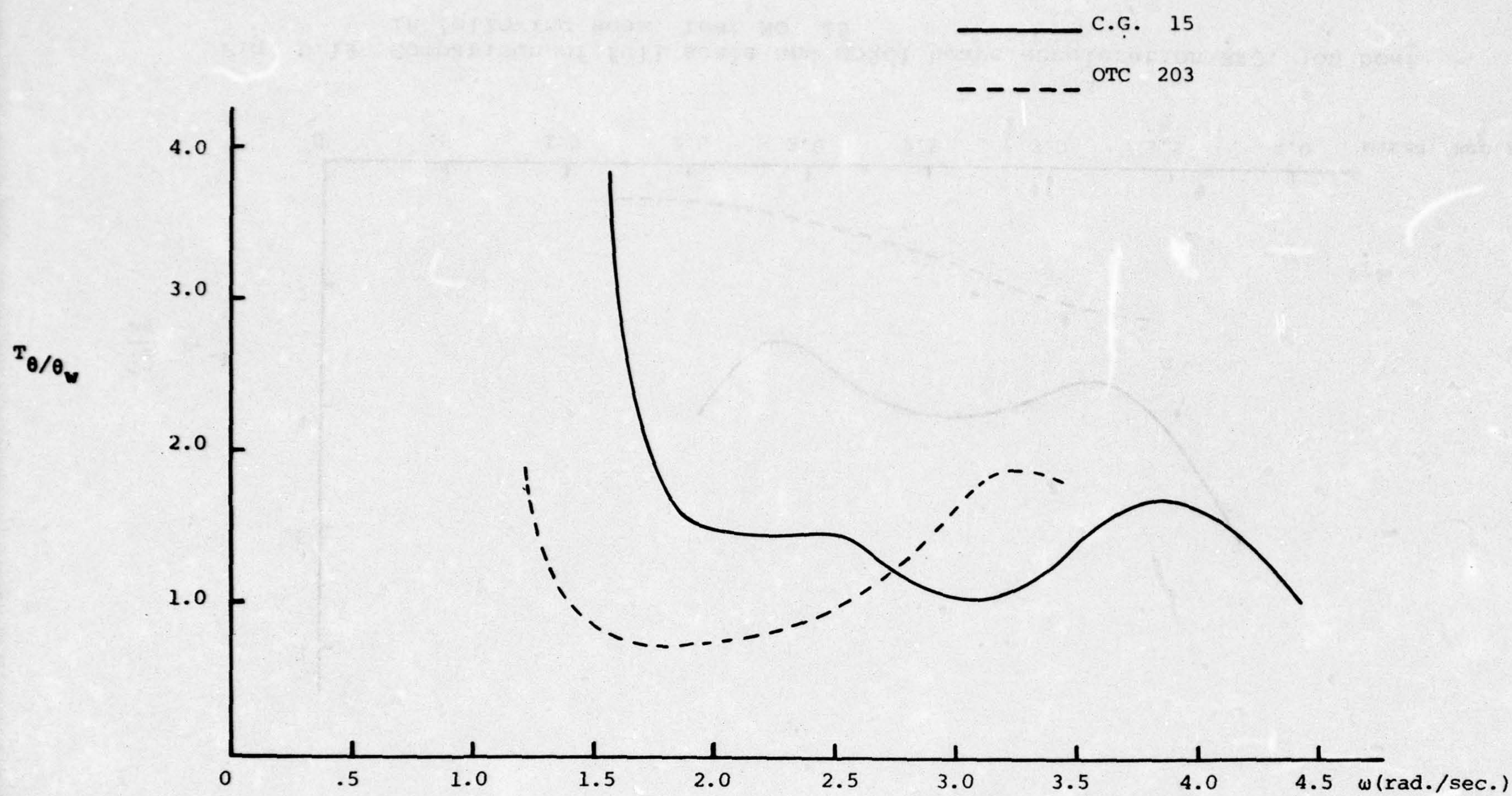

Fig. D.18 Comparison of full scale and model pitch angle RAO, jon boat in following seas, Test No. 15

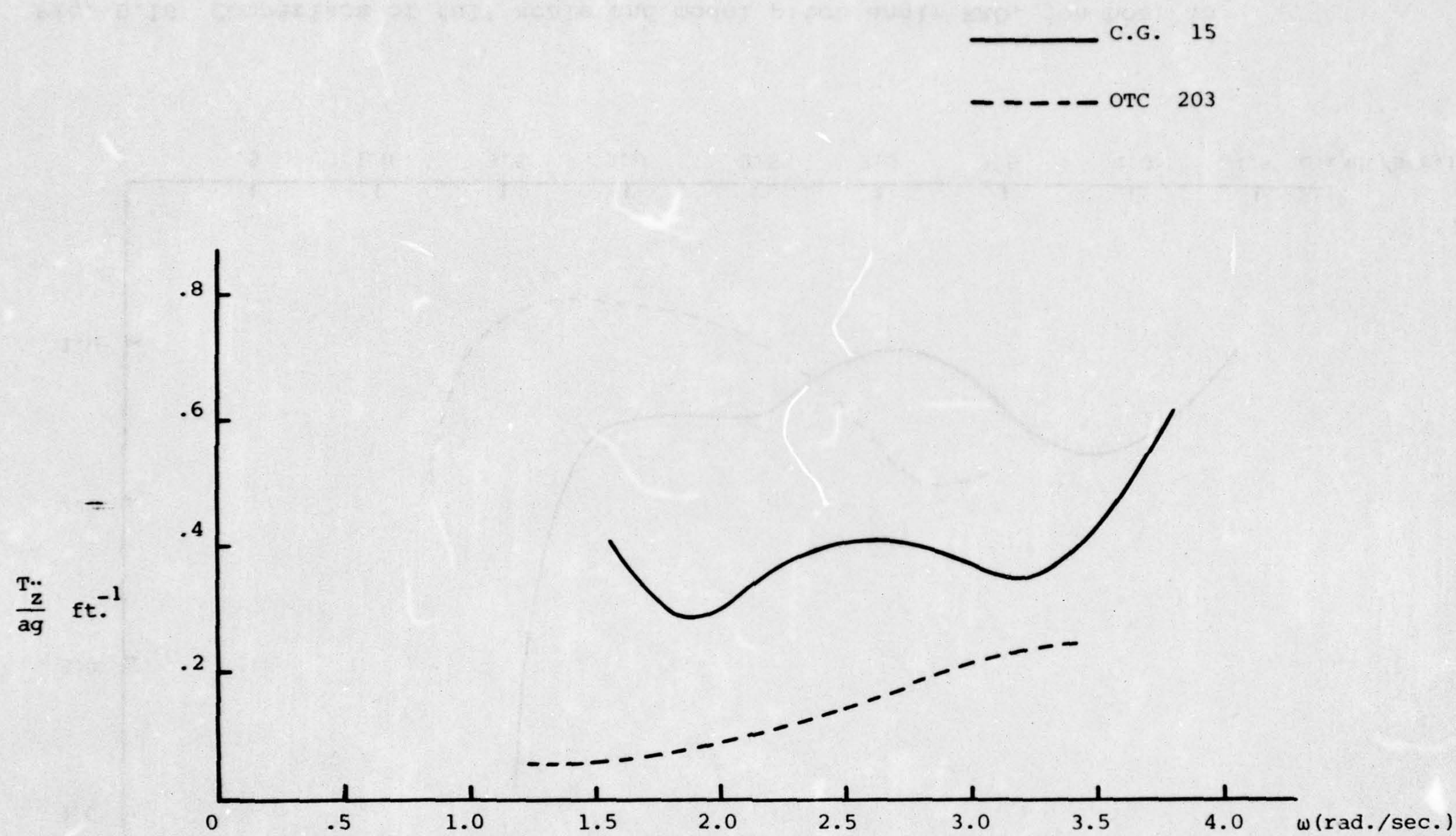

Fig. D.19 Comparison of full scale and model heave acceleration RAO, jon boat in following seas, Test No. 15

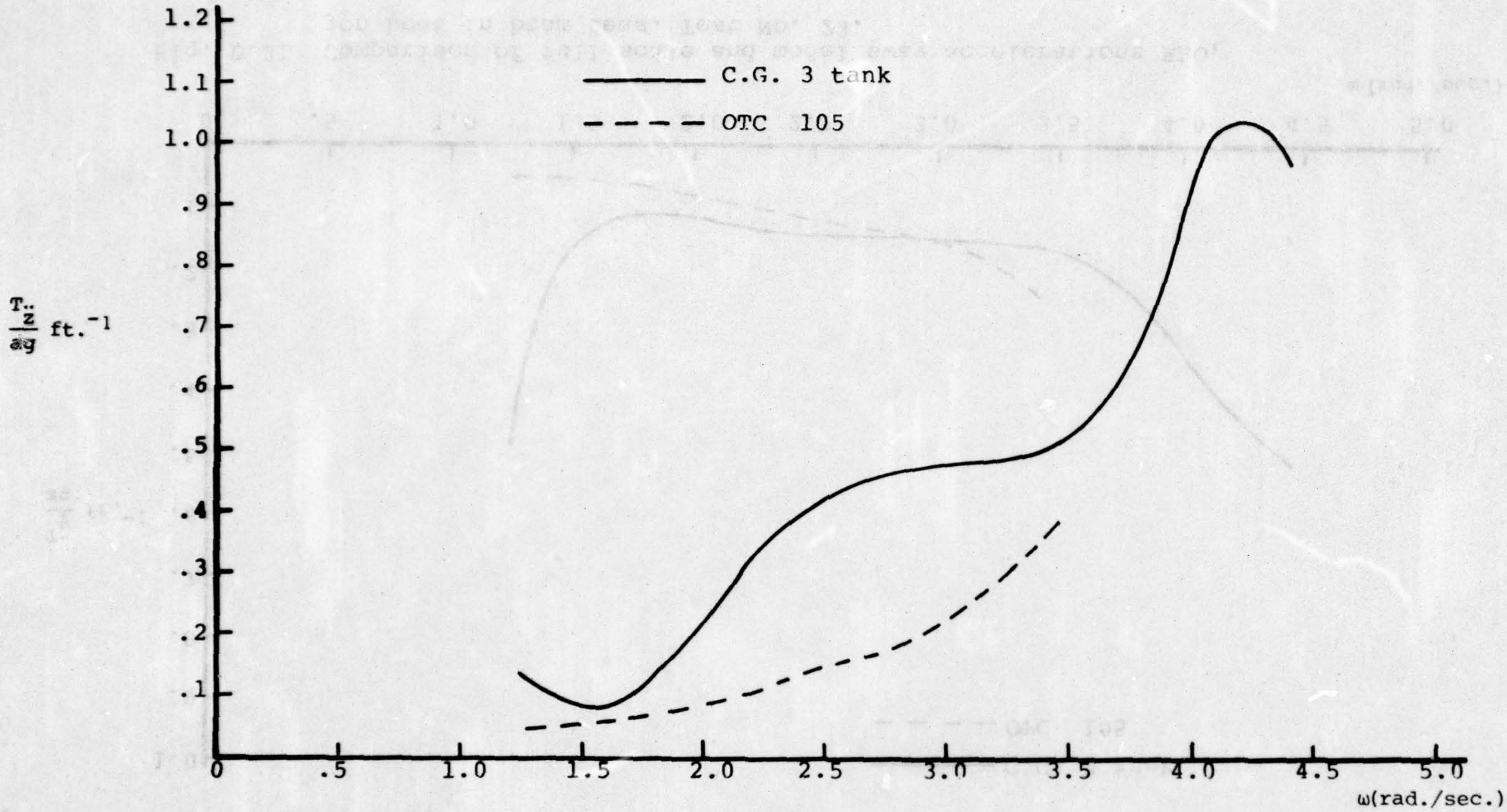

Fig. D.20 Comparison of full scale and model heave acceleration RAO, jon boat in beam seas, Test No. 23.

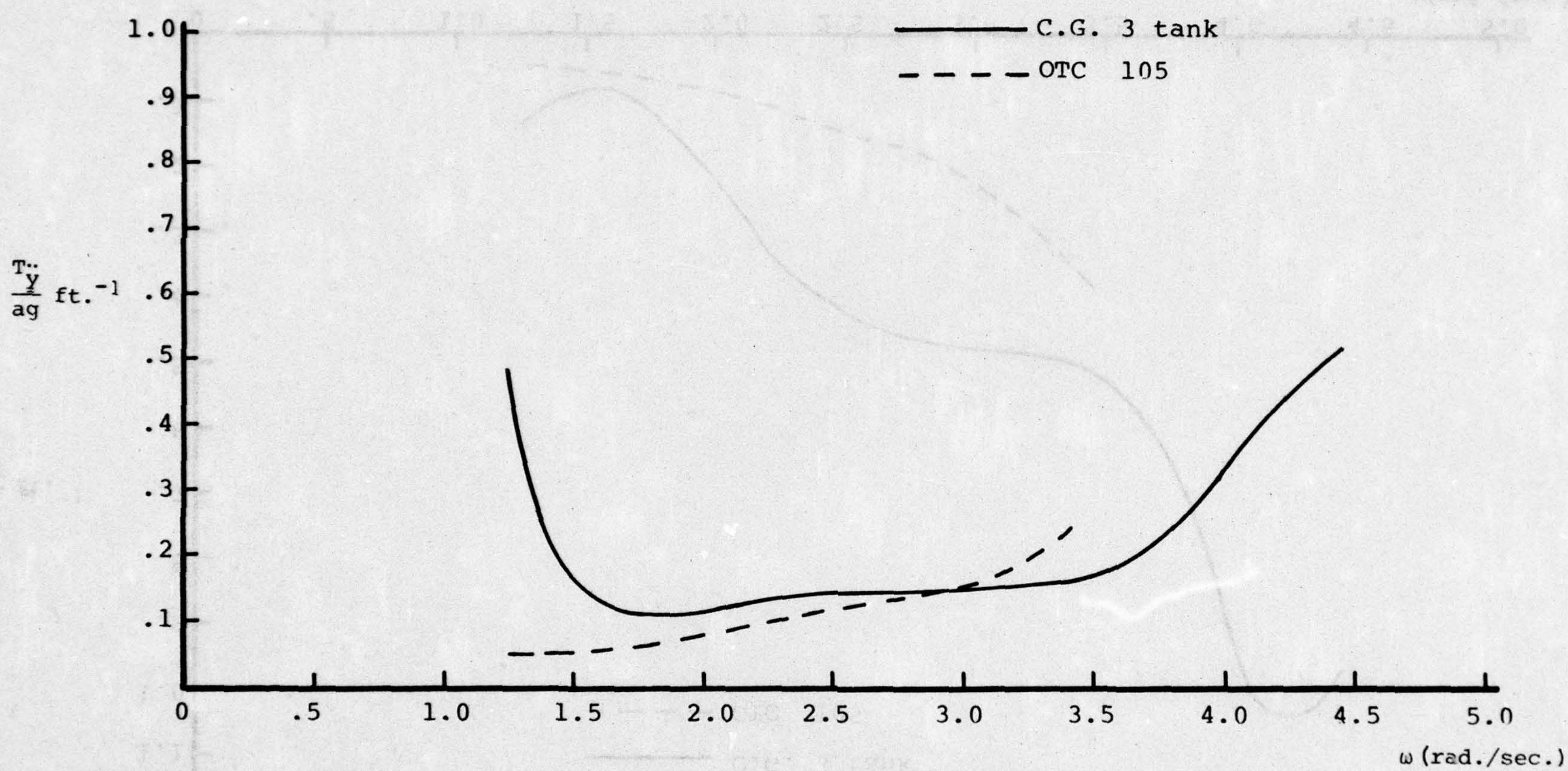

Fig. D.21 Comparison of full scale and model sway accelerations RAO, jon boat in beam seas, Test No. 23.

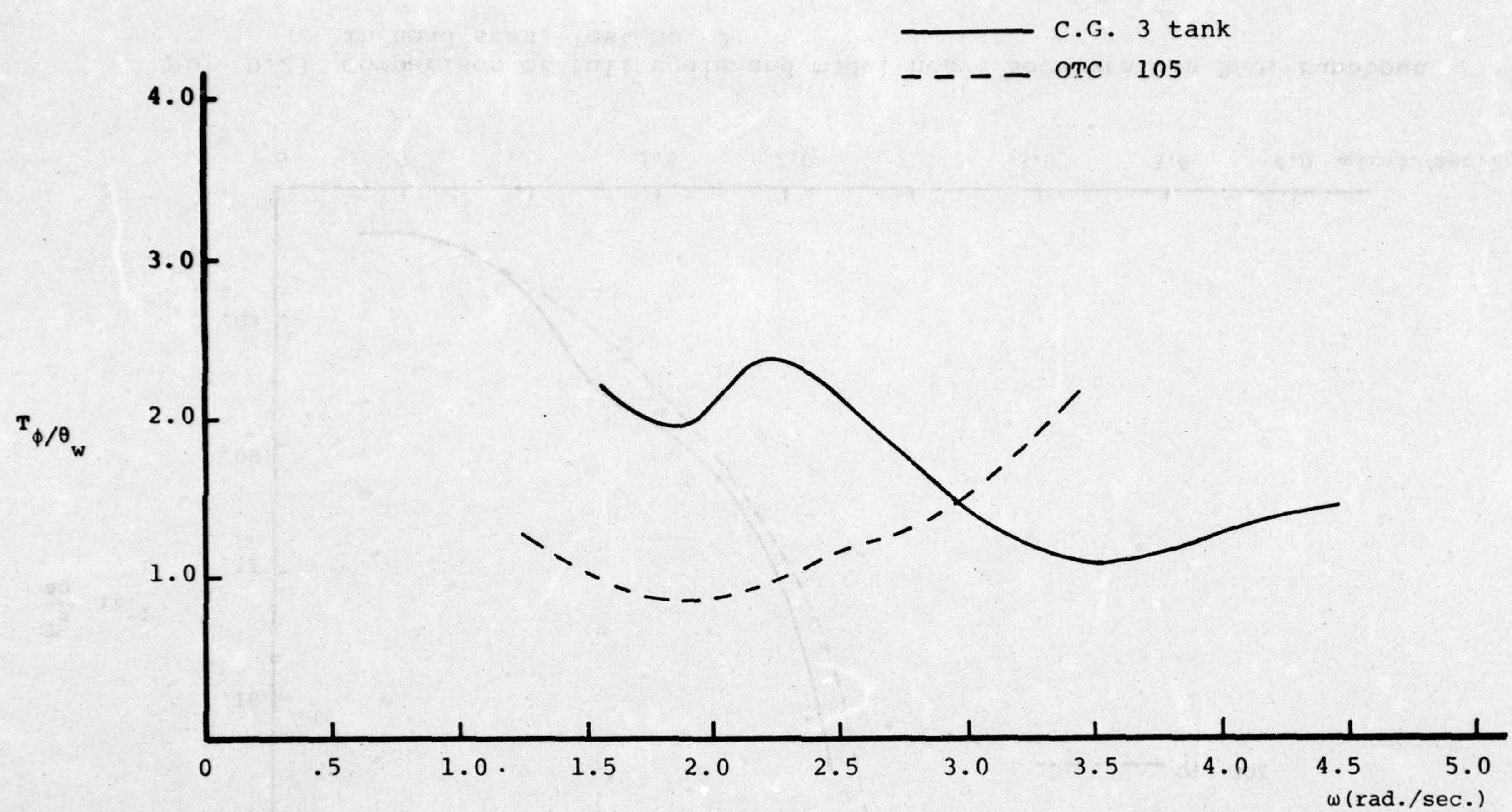

Fig. D.22 Comparison of full scale and model roll angle RAO, jon boat in beam seas, Test No. 23.

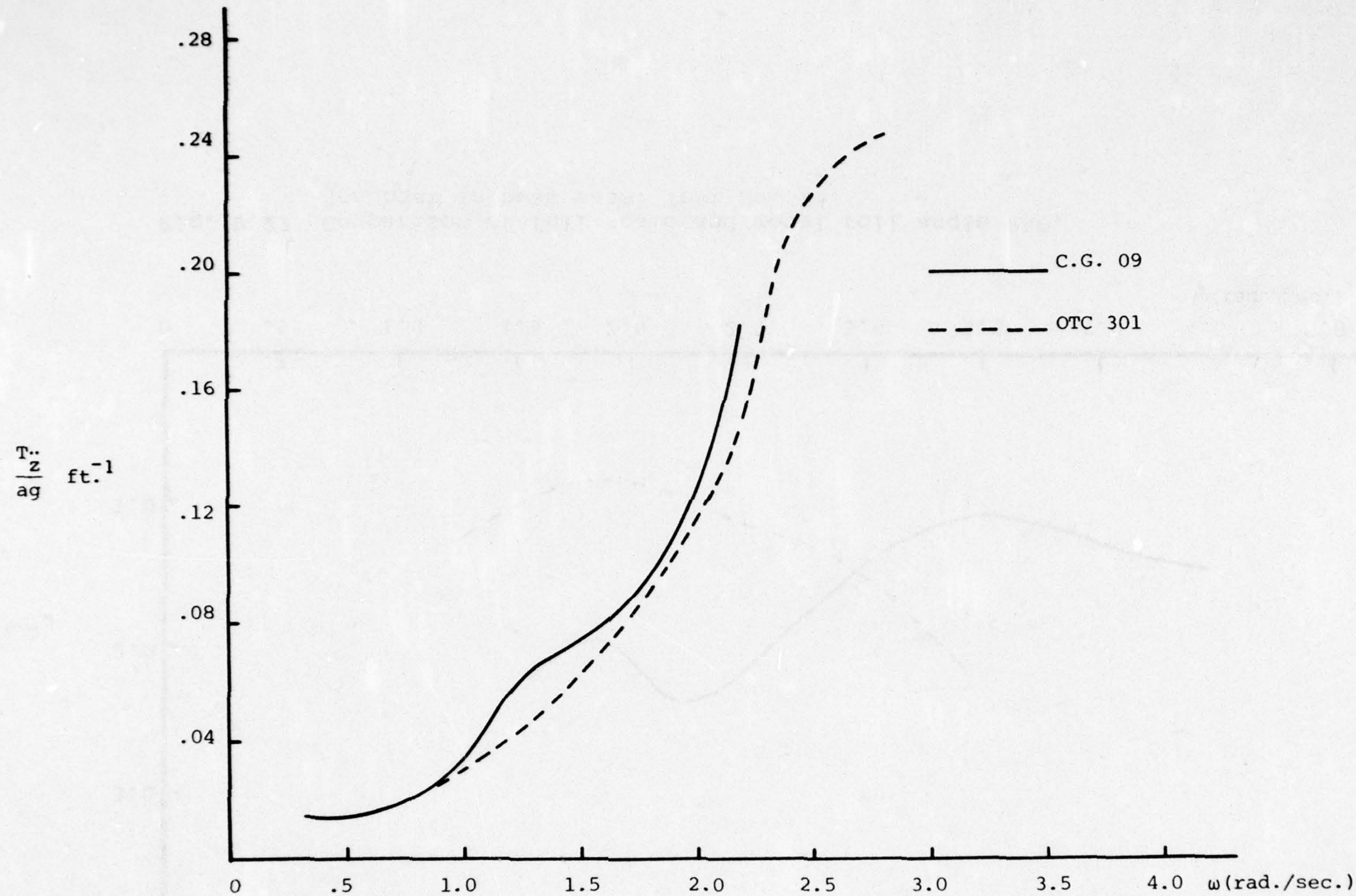

Fig. D.23 Comparison of full scale and model heave acceleration RAO, runabout in head seas, Test No. 9

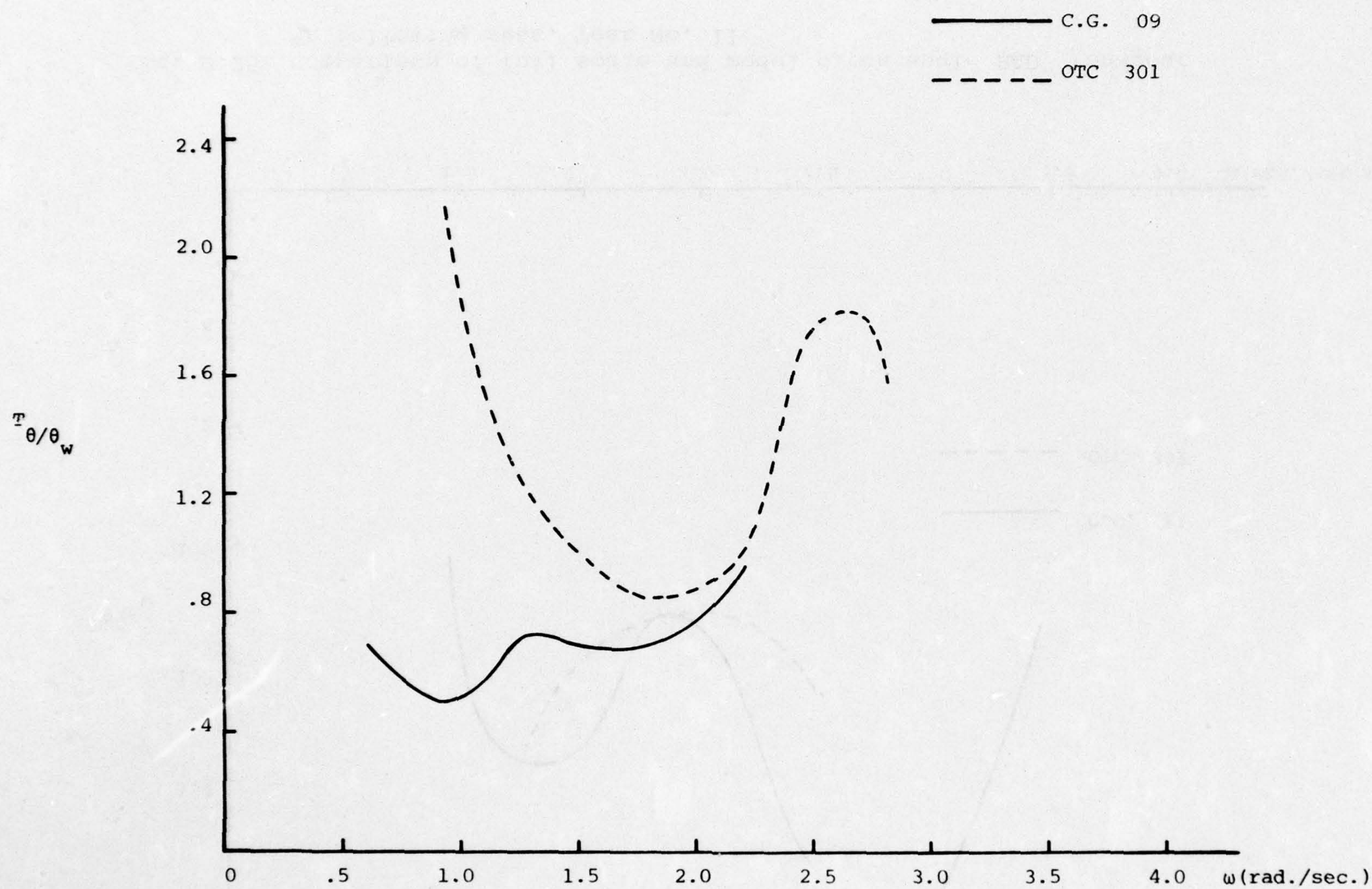

Fig. D.24 Comparison of full scale and model pitch angle RAO, runabout in head seas, Test No. 9

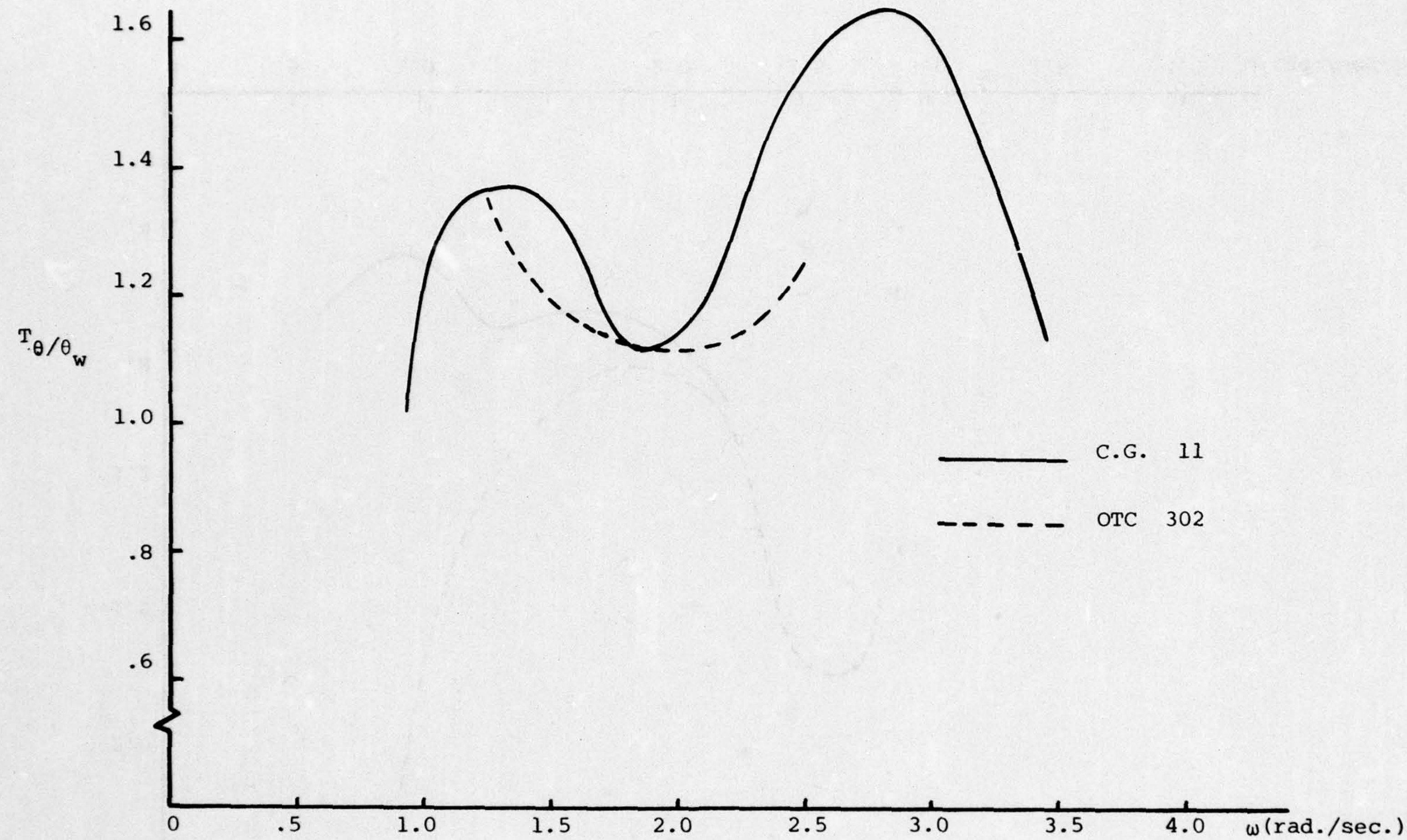

Fig. D.25 Comparison of full scale and model pitch angle RAO, runabout in following seas, Test No. 11

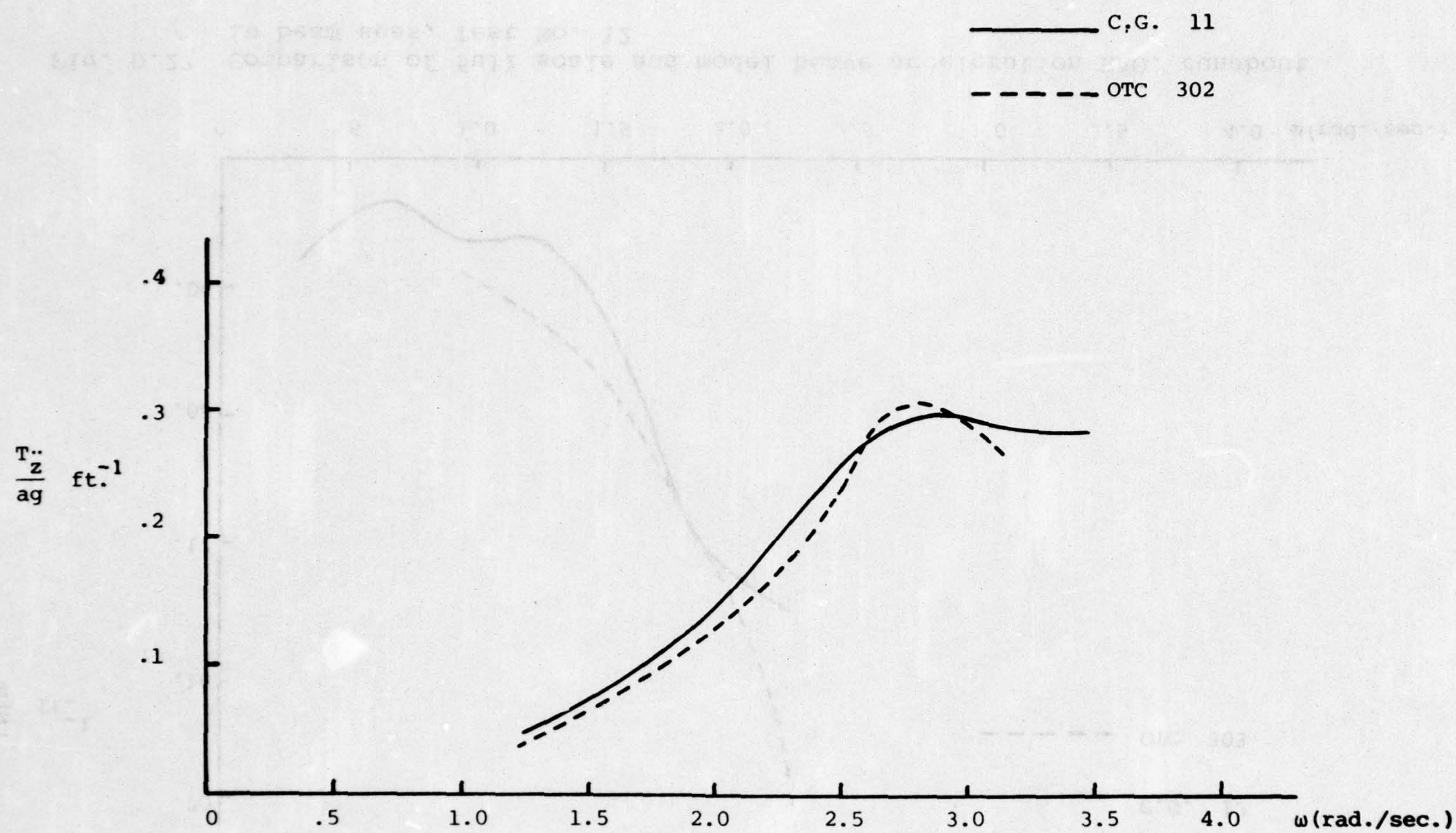

Fig. D.26 Comparison of full scale and model heave acceleration RAO runabout in following seas, Test No. 11

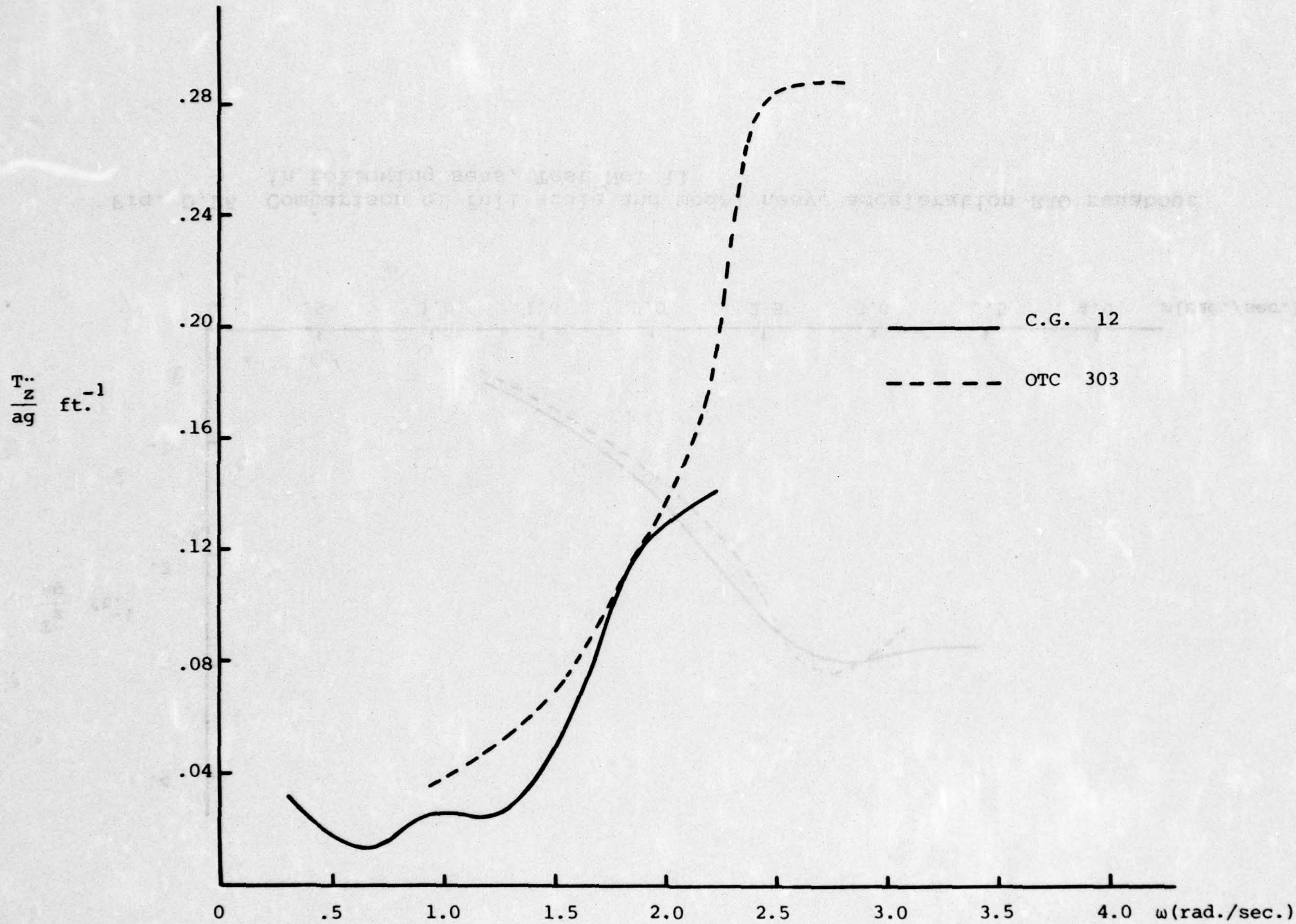

Fig. D.27 Comparison of full scale and model heave acceleration RAO, runabout in beam seas, Test No. 12

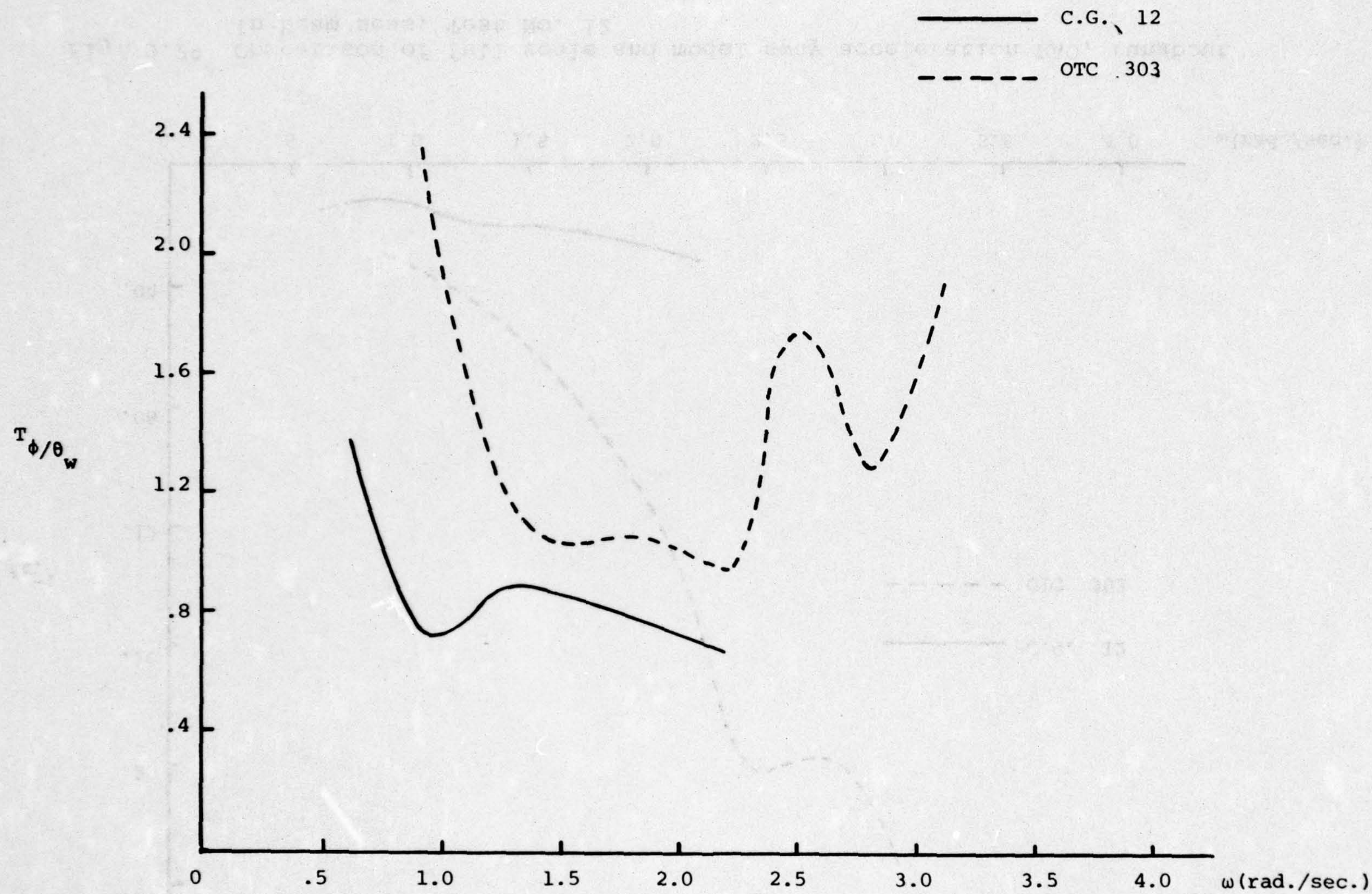

Fig. D.28 Comparison of full scale and model roll angle RAO, runabout in beam seas, Test No. 12

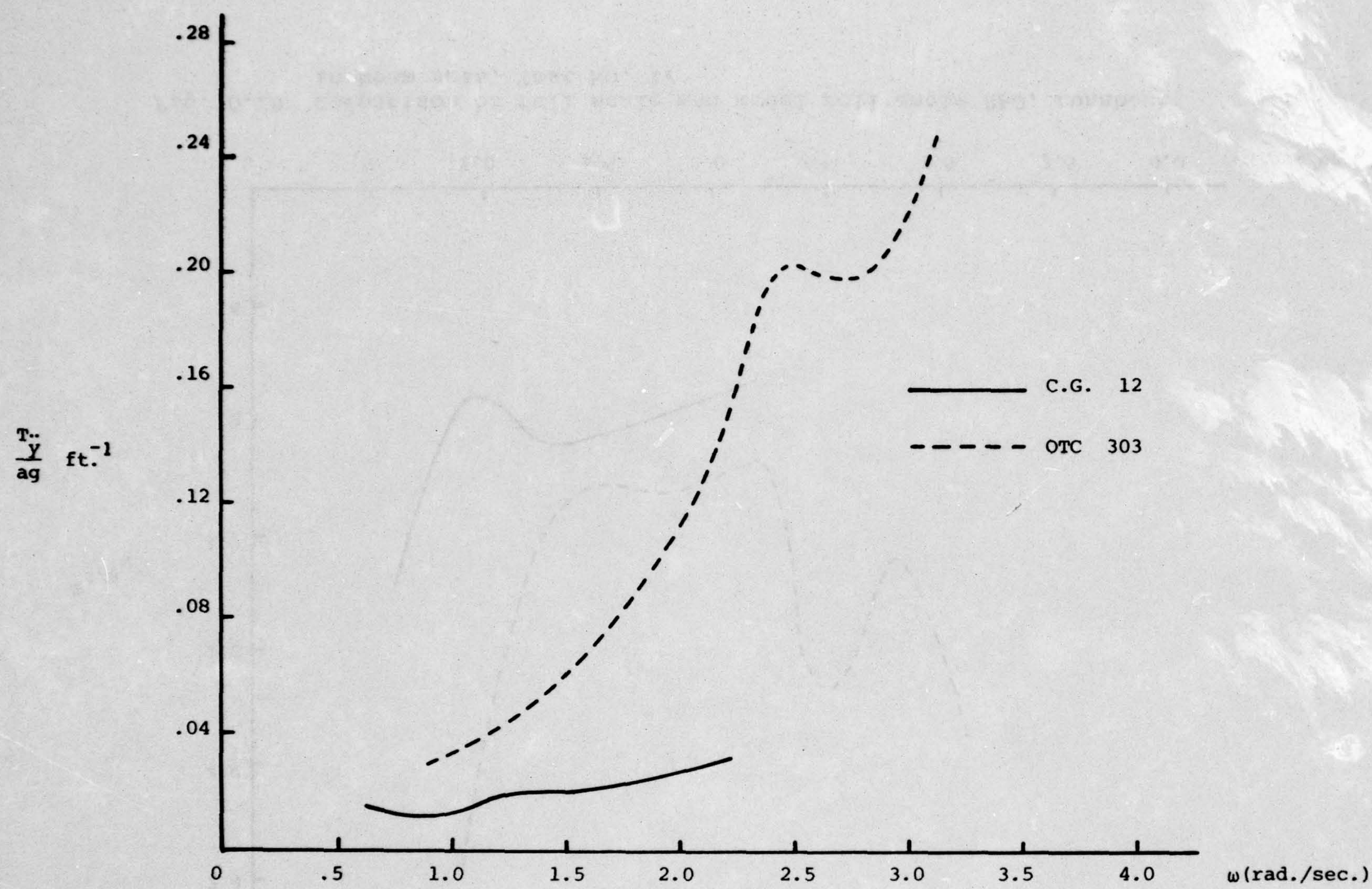

Fig. D.29 Comparison of full scale and model sway acceleration RAO, runabout in beam seas, Test No. 12

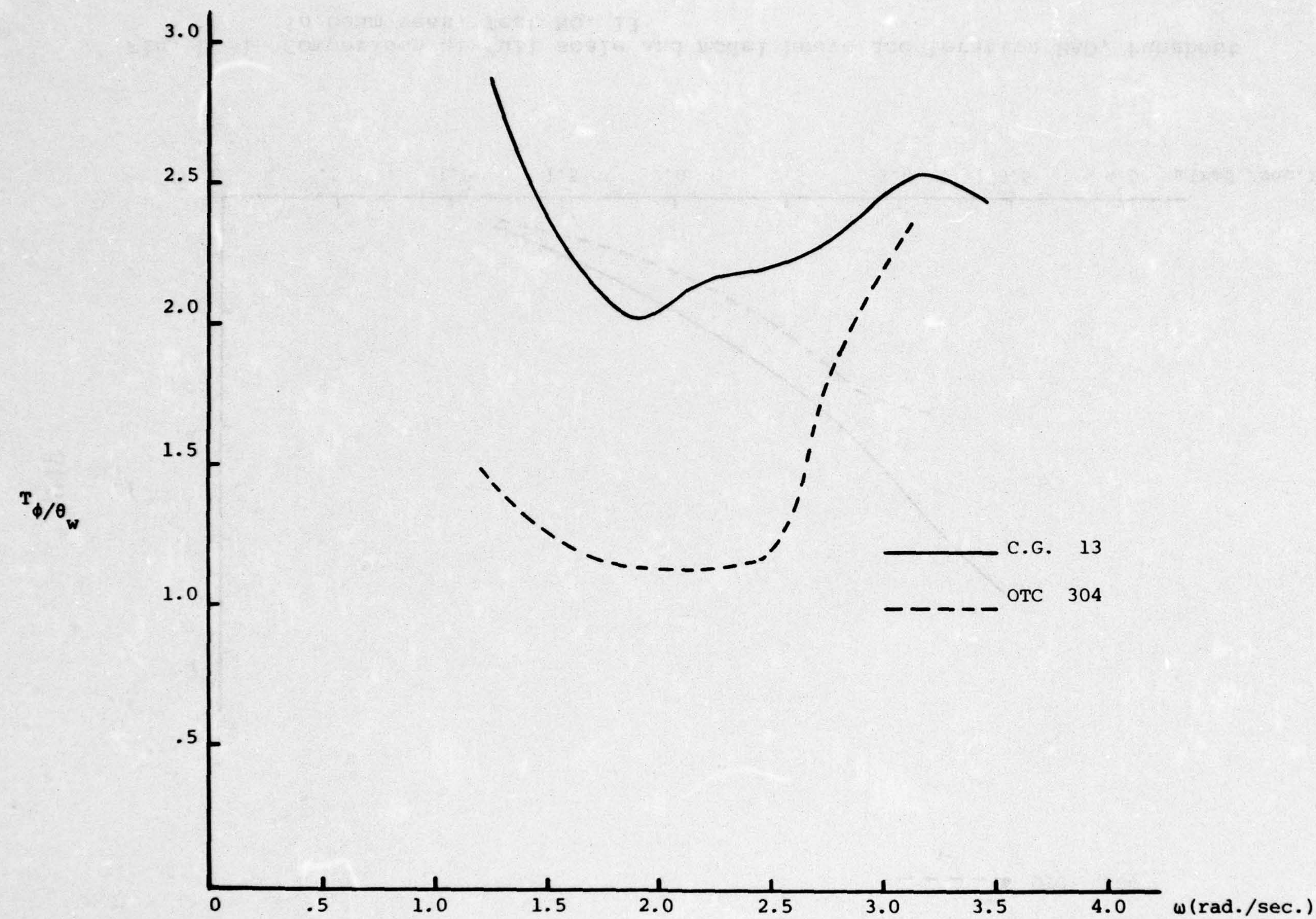

Fig. D.30 Comparison of full scale and model roll angle RAO, runabout in beam seas, Test No. 13

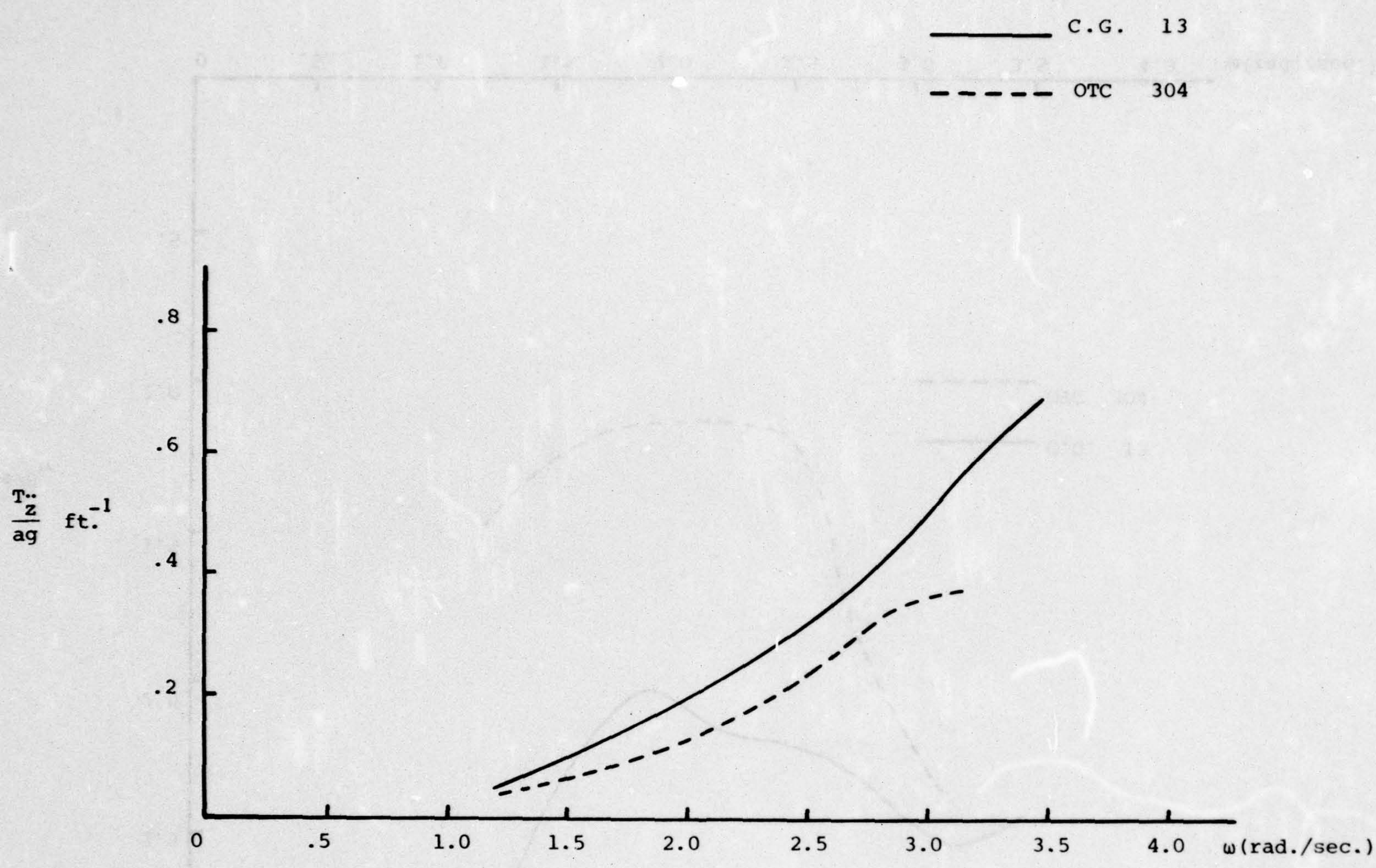

Fig. D.31 Comparison of full scale and model heave acceleration RAO, runabout in beam seas, Test No. 13

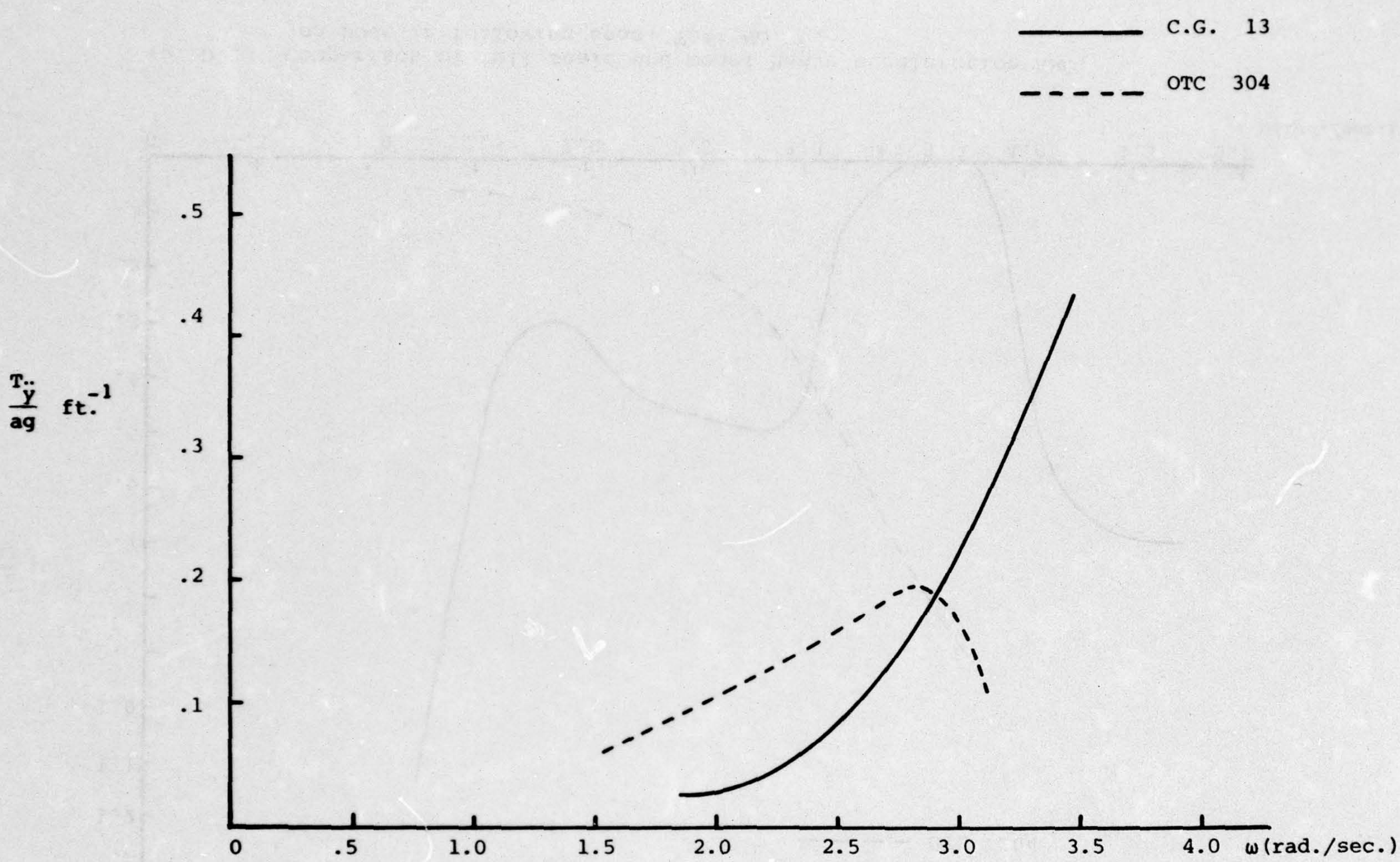

Fig. D.32 Comparison of full scale and model sway acceleration RAO, runabout in beam seas, Test No. 13

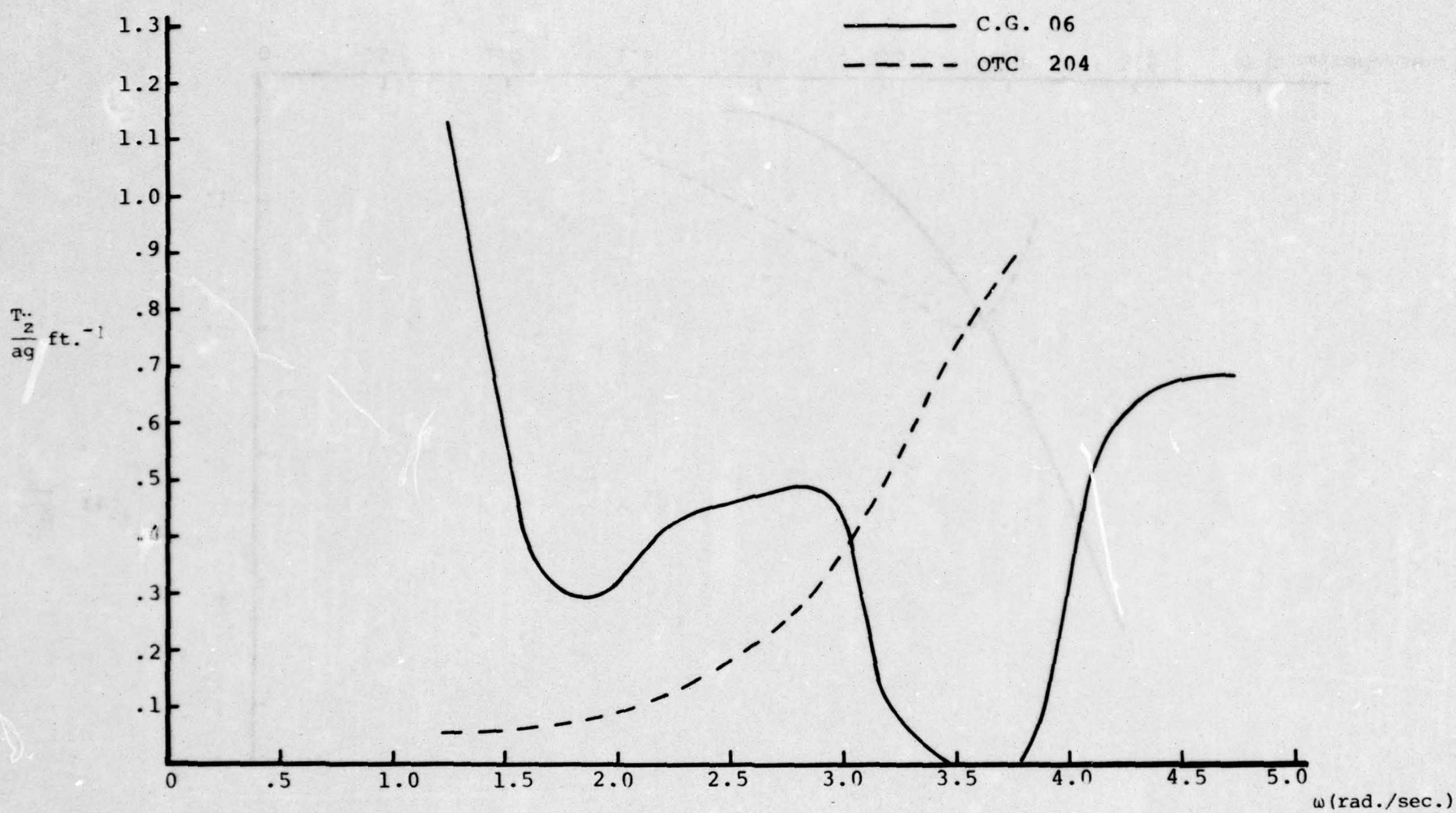

Fig. D.33 Comparison of full scale and model heave acceleration ARO, jon boat in following seas, Test No. 6.

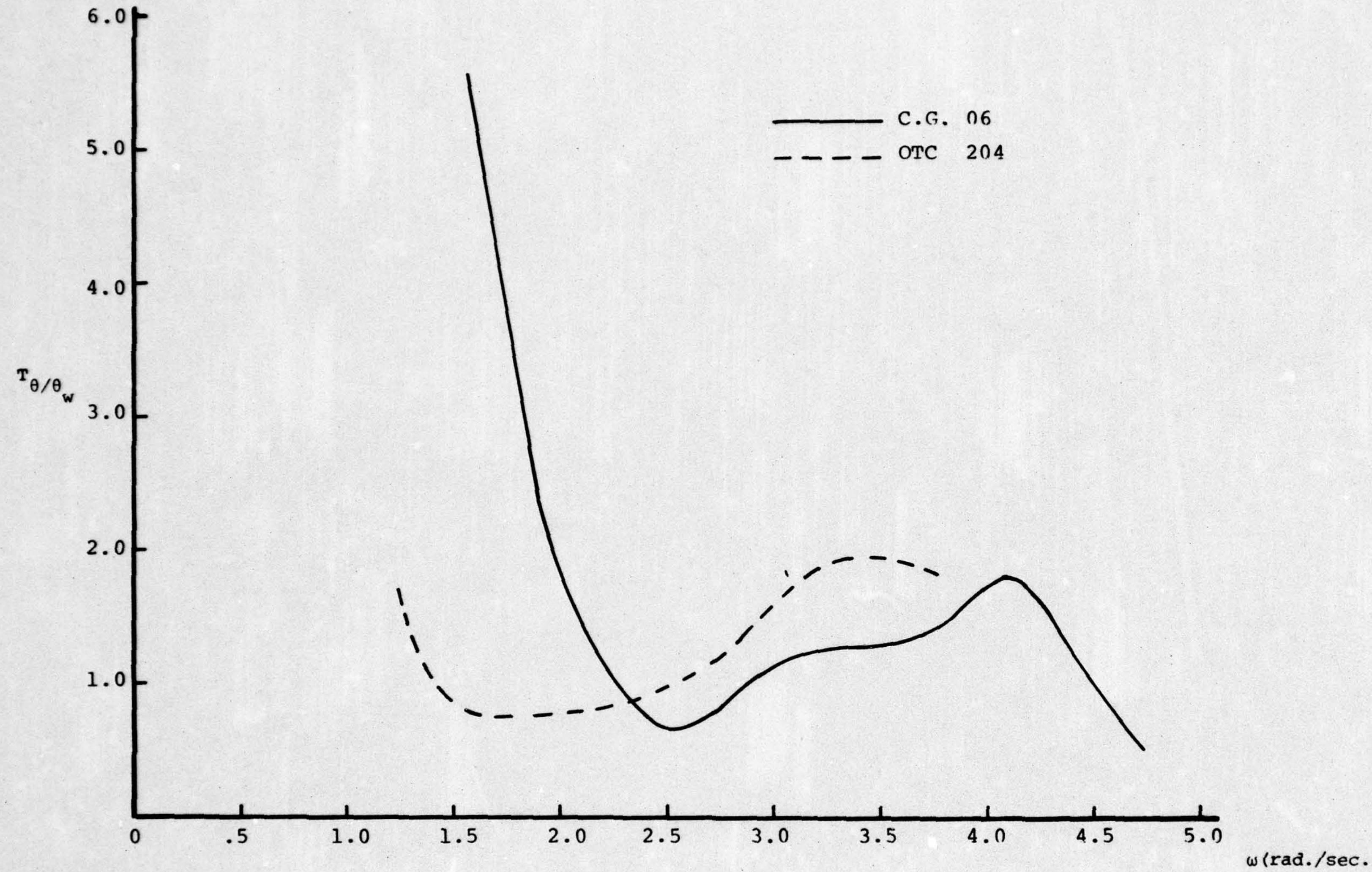

Fig. D.34 Comparison of full scale and model pitch angle RAO, jon boat in following seas, Test No. 6.

APPENDIX E

NORMALIZED STANDARD ERRORS FOR SPECTRAL COMPUTATION

APPENDIX E

Table

NORMALIZED STANDARD ERRORS

Wave Spectra

Run	N	m	ε	Δt
1	1200	20	.129	.5
2	896	20	.149	.5
9	1200	20	.129	.5
11	1200	20	.129	.5
12	600	20	.183	.5
14	1200	20	.129	.5
15	1200	20	.129	.5
Tank Tests				
101	1536	32	.144	.31622
103	1536	32	.144	.31622
105	1536	32	.144	.31622
106	1536	32	.144	.31622
201	1536	32	.144	.31622
202	1536	32	.144	.31622
203	1536	32	.144	.31622
205	1536	32	.144	.31622
206	1536	32	.144	.31622
301	1536	32	.144	.31622
302	1536	32	.144	.31622
303	1536	32	.144	.31622
304	1536	32	.144	.31622

FULL SCALE TESTS

Run	N	m	ε	Δt
1	1500	25	.129	.4
3	1425	25	.132	.4
4	600	25	.204	.4
7	1425	25	.132	.4
8	100	25	.500	.4
9	1350	25	.136	.4
11	1350	25	.136	.4
12	825	25	.174	.4
13	1650	25	.123	.4
14	250	25	.310	.4
15	175	25	.378	.4
16	1500	25	.129	.4
23	1275	25	.140	.4
24	1275	25	.140	.4
25	2700	25	.096	.4
26	2850	25	.094	.4

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